

MEASUREMENT OF TRACK-BASED MISSING TRANSVERSE MOMENTUM IN PROTON-PROTON
COLLISIONS AT $\sqrt{s} = 8$ TeV CENTRE-OF-MASS ENERGY WITH THE ATLAS DETECTOR

CLAIRE ALEXANDRA LEE

A DISSERTATION
PRESENTED TO THE FACULTY OF SCIENCE
UNIVERSITY OF JOHANNESBURG
IN CANDIDACY FOR THE DEGREE
OF DOCTOR OF PHILOSOPHY

ADVISERS:

SIMON H. CONNELL (UNIVERSITY OF JOHANNESBURG, SOUTH AFRICA)

RACHID MAZINI (ACADEMIA SINICA, TAIWAN)

AND

KETevi A. ASSAMAGAN (BROOKHAVEN NATIONAL LABORATORY, USA)

2014



© Copyright by Claire Alexandra Lee, 2014.

All rights reserved.

Abstract

The missing transverse momentum ($\mathbf{E}_T^{\text{miss}}$) in experiments at particle colliders such as the Large Hadron Collider (LHC) at CERN is defined as the momentum imbalance in the plane transverse to the beam axis: the resultant of the negative vectorial sum of the momenta of all the particles that are involved in the pp collision of interest. The reconstruction of the $\mathbf{E}_T^{\text{miss}}$ to the high precision necessary for physics analyses involves combining contributions from the fully reconstructed and calibrated hard objects in the event, most of which rely on energy measurements in the calorimeters to provide some or all of the information about the object. Additionally, contributions from particles that do not pass the hard object $\mathbf{p}_T$ thresholds form a “soft” term which is traditionally built using the topological clusters from unmatched energy deposits in the calorimeter, a method which has historically served collider experiments well, but one which is susceptible to fluctuations from noise and particles from additional, unrelated collisions within the same event. In this thesis we document the development of a new approach to the missing transverse momentum reconstruction within the ATLAS experiment, using only charged particle tracks reconstructed by the ATLAS Inner Detector to provide us with a tracks-only measurement of the missing transverse momentum which we denote $\mathbf{p}_T^{\text{miss}}$. An optimised track selection procedure was developed and used to select only high quality tracks originating from the signal pp collision vertex to form the equivalent soft term of the $\mathbf{p}_T^{\text{miss}}$. For hard objects such as electrons, muons, and jets, two methods are investigated: one using the tracks-only approach, and the other using the reconstructed, calibrated objects as used by the $\mathbf{E}_T^{\text{miss}}$. The combination of the tracks-only based soft term and the hard objects together form what we call the nominal and object-corrected versions of the $\mathbf{p}_T^{\text{miss}}$ respectively. Detailed studies of the $\mathbf{p}_T^{\text{miss}}$ algorithms were performed on 8 TeV pp collision data collected during the LHC 2012 run and are presented here. These studies, which cover the performance of the $\mathbf{p}_T^{\text{miss}}$ in various event configurations and comparisons with Monte Carlo predictions, demonstrate a robustness of the $\mathbf{p}_T^{\text{miss}}$ against the same noise and pileup fluctuations that threaten the $\mathbf{E}_T^{\text{miss}}$; a result that has already garnered the use of the $\mathbf{p}_T^{\text{miss}}$ in a number of ATLAS physics analyses.

Acknowledgements

The last few years have given me a host of wonderful opportunities: to be part of the forming of the South African cluster on ATLAS, to collaborate with numerous people from many different universities and institutes worldwide, and to be able to spend the past three years at CERN, all of which have contributed to an experience that shall remain unrivalled in my life. I would therefore like to take the opportunity to thank some of the many individuals who have supported me throughout my PhD (though this is by no means an exhaustive list).

Firstly, I would like to thank my thesis advisors, Simon H. Connell, Kétévi A. Assamagan, and Rachid Mazini, for the opportunity to work and learn from you all, and for the encouragement along the way. Simon, you have been a colleague and a friend for a long time, and your love of experimental physics was what got me hooked and keeps me going to this day. Kétévi, thank you for seeing the chance to get South African universities involved in the ATLAS experiment, for supporting us in our teething years, and for your knowledge which you so welcomingly share with us. And Rachid, for your constant support and companionship over the past three years, both inside CERN and out, I am most deeply grateful (and Cabhán thanks you for all the ice creams!).

On behalf of myself and the UJ-ATLAS group I would like to thank the South African Department of Science and Technology (DST), and the National Research Foundation (NRF), for providing us with the opportunity to be part of this fantastic worldwide collaboration, with the founding of the South Africa-CERN Programme (SA-CERN) that has allowed South Africa to truly become an important player in the world of High Energy Physics. Thank you also to Brookhaven National Laboratory (BNL) for helping South Africa through the transitional period between starting work on ATLAS and becoming an official institute of the ATLAS Collaboration. And of course, to CERN for the very successful operation of the LHC, and the ATLAS funding agencies, institutes and support staff, without whom none of this could be possible.

Personally I would also like to thank the many wonderful people within SA-CERN whom I have had the pleasure to meet and work with over the past few years, and send my encouragement to all the students working on their MSc and PhD degrees through CERN. And to the University of Johannesburg Physics Department (and in particular Aletta, André, Doomnull, Elizabeth, Jono,

Lianie, Martin and Mathieu) thank you for your support, encouragement, and friendship over these past years.

To all at my secondary institute, Academia Sinica, it has been an honour working with you all, and I am deeply grateful to Prof. Lee for allowing me this opportunity. Special thanks must go to David and Song-Ming, for their eternal patience and help solving everything from the most mundane to the most complex of issues. And to Bo, it has been wonderful working alongside you, and I wish you all the best for your PhD. I'd also like to say a special thank you to Jhen-Wei, for his tireless work keeping the Taiwan cluster online and all his help troubleshooting any issues I had.

To my friends and colleagues in the Jet/ E_T^{miss} group in ATLAS, especially the convenors Michael and David, thank you for the time that I was able to spend learning from you all, for the meetings and workshops and emails and general good times, and special thanks to Caterina, Irene, Paolo, Rosa, and TJ from the E_T^{miss} group. To everyone from the LAr team, especially the experts and most especially Andrew, Claire, Hass, Hector, Olivier and Richard, thank you for the great times we had over at Point 1.

To the ATLAS TDAQ sysadmins, thank you all for your wonderful friendship over the past few years, and for putting up with a physicist in your midst! And of course, for the thankless job keeping our detector in safe and working order, even when everyone else is on holiday.

To all the wonderful people I have met through various outreach activities at CERN, thank you all for the laughs and inspiration, and for helping me stay sane when coding becomes too much! I'd like to mention specially the 2013 "Bad Sauna" FameLab Finalists, the TEDxCERN 2013 and 2014 teams, and the Comedy Collider crew, for the wonderful memories we have together.

To all my unnamed friends, ATLAS and not, around the world, who have helped me in various ways, I am grateful for all the times our world lines have crossed. And to Alex, Gordon, Robert and Sahal, who have become some of my closest friends, thank you all for your friendship and support, most especially over this past year.

To my wonderful, huge, crazy family spread over the UK and South Africa, thank you for the support, love and laughter over all these years. To John and Joey, thank you for letting me steal your son and grandson away from you - I know it was difficult to let go - and for your support whilst here. An extra special thank you must go to my parents, Greg and Karen, for everything you have ever done for me, and instilling in me a love of the search for knowledge since I was a child. Because of you, I am proud to be the person I am today.

And finally, to my two most special people, my husband Chris and my son Cabhán, thank you putting up with me, following me around the world, and for your love and support on a daily basis that makes every day worthwhile.

To Dad,
for teaching me the beauty of curiosity
and always encouraging me to use it.

Contents

Abstract	iii
Acknowledgements	iv
List of Tables	xii
List of Figures	xiv
Preface	1
1 Introduction	5
2 Theory of Physics at the LHC	11
2.1 The Standard Model of Particle Physics	11
2.2 Hadron Collider Physics	16
2.2.1 Parton distributions within the proton	18
2.2.2 W and Z physics at the LHC	19
2.2.2.1 Production mechanisms	21
2.2.2.2 Decay channels	23
2.2.2.3 W and Z boson cross sections at the LHC	24
2.3 Monte Carlo Generators	26
3 The LHC and ATLAS at CERN	29
3.1 A Brief History of CERN	29
3.1.1 The Large Hadron Collider project	30
3.1.2 The ATLAS collaboration	30
3.2 The LHC at Present	31
3.2.1 Luminosity	33

3.3	The ATLAS Detector	36
3.3.1	The Inner Detector (ID)	38
3.3.2	The Electromagnetic and Hadronic calorimeters	40
3.3.3	The Muon Spectrometer (MS)	41
3.4	Data and Monte Carlo Samples for the 2012 LHC Run	42
4	Track-Based Missing Transverse Momentum in ATLAS	45
4.1	Motivation	46
4.2	Limitations	47
4.3	Physics Object Selection	47
4.3.1	Primary vertex and general track selection	47
4.3.1.1	Tracks surrounding high $\mathbf{p}_T$ reconstructed electrons	49
4.3.1.2	Tracks in dense, high $\mathbf{p}_T$ jets	49
4.3.1.3	Tracks with very large momentum	50
4.3.2	Lepton selection	52
4.3.3	Jet selection	53
4.4	$\mathbf{p}_T^{\text{miss}}$ Reconstruction	53
4.4.1	Nominal $\mathbf{p}_T^{\text{miss}}$	54
4.4.2	Object-corrected $\mathbf{p}_T^{\text{miss}}$	55
4.5	$\mathbf{E}_T^{\text{miss}}$ Reconstruction	56
5	Performance of Track-based Missing Transverse Momentum	59
5.1	Event Selections	60
5.1.1	$Z \rightarrow \ell\ell$ event selection	60
5.1.2	$W \rightarrow \ell\nu$ event selection	61
5.1.3	$Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ event backgrounds	61
5.2	Overview of the $\mathbf{p}_T^{\text{miss}}$ Distributions	63
5.2.1	Basic nominal $\mathbf{p}_T^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$ events	63
5.2.2	$\mathbf{p}_T^{\text{miss}}$ in the muon and electron channels	66
5.2.3	The effect of jets in the event	68
5.2.4	The object-corrected $\mathbf{p}_T^{\text{miss}}$	69
5.2.5	Correlation between $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$	73
5.3	Comparison of $\mathbf{p}_T^{\text{miss}}$ Distributions in Data and Monte Carlo Simulation	74

5.3.1	$\mathbf{p}_T^{\text{miss}}$ distributions in $Z \rightarrow \ell\ell$ events	75
5.3.2	$\mathbf{p}_T^{\text{miss}}$ distributions in $W \rightarrow \ell\nu$ events	76
5.4	$\mathbf{p}_T^{\text{miss}}$ Performance with respect to Event Activity	83
5.4.1	$\mathbf{p}_T^{\text{miss}}$ x and y Resolution	83
5.4.2	Directional Resolution	85
5.5	$\mathbf{p}_T^{\text{miss}}$ Response	85
5.5.1	Final states with no real $\mathbf{E}_T^{\text{miss}}$ (scale in $Z \rightarrow \ell\ell$ events)	87
5.5.2	Final states with real $\mathbf{E}_T^{\text{miss}}$ (linearity of $W \rightarrow \ell\nu$ events)	90
5.5.3	Reconstruction of mass in final states with $\mathbf{E}_T^{\text{miss}}$ ($W \rightarrow \ell\nu$)	92
5.6	$\mathbf{p}_T^{\text{miss}}$ Systematics	94
6	$\mathbf{p}_T^{\text{miss}}$ in Physics Analyses and Future Developments	97
6.1	$\mathbf{p}_T^{\text{miss}}$ in ATLAS Physics Analyses	97
6.1.1	$\mathbf{p}_T^{\text{miss}}$ in the $H \rightarrow WW$ analysis	97
6.1.2	$\mathbf{p}_T^{\text{miss}}$ in the $H \rightarrow b\bar{b}$ analysis	101
6.1.3	Photons in $\mathbf{p}_T^{\text{miss}}$	101
6.2	Future Developments	104
7	Conclusions and Outlook	105
A	Development of the Standard Model	109
A.1	Quantum electrodynamics	110
A.2	Quantum chromodynamics	111
A.2.1	Confinement, hadronisation, and jets at hadron colliders	112
A.3	Electroweak symmetry breaking and the Higgs sector	113
A.3.1	The Higgs boson	115
A.4	Limitations of the Standard Model	116
B	$\mathbf{p}_T^{\text{miss}}$ Reconstruction with Different MC Event Generators	117
B.1	Jet Mismodelling	117
B.2	Underlying Event Mismodelling	118
	Glossary	129
	Bibliography	133

List of Tables

2.1	Current most precise measurements of the mass and width of the W and Z bosons. .	20
2.2	Vector boson production processes at LO, NLO, and NNLO at the LHC.	22
2.3	Vector boson decay modes and measured branching ratios.	25
2.4	Theoretical NNLO production cross sections times their respective leptonic decay branching ratios for W and Z bosons at $\sqrt{s} = 8$ TeV.	25
5.1	$\mathbf{p}_x^{\text{miss}}$ and $\mathbf{p}_y^{\text{miss}}$ mean and RMS values in $Z \rightarrow \mu\mu$ Data and signal Monte Carlo . . .	65
5.2	$\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ mean and RMS values in $Z \rightarrow \mu\mu$ Data and signal Monte Carlo . . .	72
5.3	$\mathbf{p}_T^{\text{miss}}$ resolution and ΣE_T fit values	85

List of Figures

1.1	Overall view of CERN and the LHC.	6
1.2	Display of a Higgs boson candidate event in the $b\bar{b}$ channel with zero selected leptons.	8
2.1	The set of fundamental particles comprising the Standard Model today.	12
2.2	Schematic illustration of the quark content of a proton.	16
2.3	Schematic illustration of a proton-proton interaction showing the production of a vector boson and the resulting underlying event contribution.	17
2.4	Parton Distribution Functions for gluons and quarks (excluding t and $\bar{t}$) at the LHC as a function of x , shown for $Q^2 = 10$ and 10^4 GeV^2	19
2.5	Production cross sections for a variety of Standard Model processes at the LHC.	20
2.6	Leading order and dominant vector boson production through the tree-level Drell-Yan channel.	21
2.7	Next-to-leading order vector boson production processes in association with 1 jet.	21
2.8	Individual quark subprocess contributions to the LO W boson and Z boson production cross sections as a function of $\sqrt{s}$	23
3.1	Diagram of the CERN Accelerator Complex.	31
3.2	Schematic of the magnetic field inside one of the LHC dipole magnets, and a simulation of the relative beam sizes around the ATLAS interaction point.	32
3.3	Cumulative luminosity versus time delivered to and recorded by ATLAS during stable beams for pp collisions at 7 and 8 TeV centre-of-mass energy in 2011 and 2012.	34

3.4	Peak number of interactions per LHC bunch crossing in 2010, 2011 and 2012; and a comparison of the mean number of interactions per bunch crossing between 2011 and 2012.	35
3.5	A candidate $Z \rightarrow \mu\mu$ event with 25 reconstructed vertices.	36
3.6	Computer-generated model of the ATLAS detector and its subsystems.	37
4.1	Track $\mathbf{p}_T$ distribution in $Z \rightarrow ee$ events from 2012 data before and after the misreconstructed track momentum rejection is applied.	51
4.2	Track selection efficiency as a function of track $\mathbf{p}_T$ and η for minimum bias, $Z \rightarrow \mu\mu$ and QCD dijet events.	51
5.1	x and y components of the nominal $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ in $Z \rightarrow \mu\mu$ inclusive and 0 jet events.	64
5.2	Nominal $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ inclusive and 0 jet events.	66
5.3	Scalar ΣE_T and Σp_T distributions for inclusive and 0 jet $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ events.	67
5.4	Comparison between the nominal $\mathbf{p}_T^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ inclusive and 0 jet events.	67
5.5	Effect of the number of jets and the jet $\mathbf{p}_T$ on the nominal $\mathbf{p}_T^{\text{miss}}$ distributions for $Z \rightarrow \mu\mu$ events.	68
5.6	Effect of the number of jets and the jet $\mathbf{p}_T$ on the object-corrected $\mathbf{p}_T^{\text{miss}}$ distributions for $Z \rightarrow \mu\mu$ events.	68
5.7	Difference between the true $\mathbf{E}_T^{\text{miss}}$ and reconstructed $\mathbf{p}_T^{\text{miss}}$ in $Z \rightarrow \mu\mu + 1$ jet events, where the jet is either central or forward.	70
5.8	Difference between the true $\mathbf{E}_T^{\text{miss}}$ and reconstructed $\mathbf{p}_T^{\text{miss}}$ as a function of the transverse momentum of the Z boson, in $Z \rightarrow \mu\mu + 1$ jet events, where the jet is either central or forward. Both nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ distributions are shown.	71
5.9	Difference between the true $\mathbf{E}_T^{\text{miss}}$ and reconstructed $\mathbf{p}_T^{\text{miss}}$ in $Z \rightarrow \mu\mu + 2$ jet events, where the jets are either both central, or one central, one forward.	72
5.10	Nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$ inclusive and 0 jet events.	73
5.11	Difference $\Delta\phi$ between the azimuthal angles of the track-based $\mathbf{p}_T^{\text{miss}}$ and calorimeter-based $\mathbf{E}_T^{\text{miss}}$ for $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ events.	74

5.12	Data-to-Monte Carlo comparisons of the x component of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$, in $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events.	77
5.13	Data-to-Monte Carlo comparisons of the y component of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$, in $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events.	78
5.14	Data-to-Monte Carlo comparisons of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$, in $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events.	79
5.15	Data-to-Monte Carlo comparisons of the nominal and object-corrected scalar Σp_T distributions in $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events.	80
5.16	Data-to-Monte Carlo comparisons of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$, in $W \rightarrow \mu\nu$ and $W \rightarrow e\nu$ events.	81
5.17	Data-to-Monte Carlo comparisons of the nominal and object-corrected scalar Σp_T distributions in $W \rightarrow \mu\nu$ and $W \rightarrow e\nu$ events.	82
5.18	Resolution of the x and y components of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ for $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events, as a function of the average number of interactions per bunch crossing $\langle\mu\rangle$	84
5.19	Resolution of the x and y components of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ for $Z \rightarrow ee$ and $W \rightarrow e\nu$ events as a function of the number of reconstructed vertices in the event and the scalar sum of the total transverse energy in the calorimeter.	84
5.20	$\Delta\phi$ width between the $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$, and between the $\mathbf{p}_T^{\text{miss}}$ or $\mathbf{E}_T^{\text{miss}}$ and the true $\mathbf{E}_T^{\text{miss}}$, as a function of the number of reconstructed vertices in $W \rightarrow \mu\nu$ events.	86
5.21	Projection of the $\mathbf{E}_T^{\text{miss}}$ along the direction of the Z boson $\mathbf{E}_T^{\text{miss}} \cdot \mathbf{A}_Z$	87
5.22	Diagnostic plot showing the mean value of the projection $\mathbf{E}_T^{\text{miss}} \cdot \mathbf{A}_Z$ as a function of the reconstructed transverse momentum of the Z boson, for the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ in $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events.	88
5.23	Diagnostic scale showing the average percentage of the hadronic event activity reconstructed by the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ as a function of the transverse momentum of the Z boson.	89
5.24	Diagnostic scale showing the average percentage of the hadronic event activity reconstructed by the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ as a function of the transverse momentum of the Z boson, for various values of the jet transverse momentum.	90
5.25	Mean value of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ as a function of true $\mathbf{E}_T^{\text{miss}}$ in $W \rightarrow \mu\nu$ events.	91

5.26	Nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ linearity with respect to the true $\mathbf{E}_T^{\text{miss}}$ in $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ events.	91
5.27	Missing transverse momentum and transverse mass distributions in $W \rightarrow e\nu$ events.	92
5.28	Linearity of the W mass calculated using the nominal $\mathbf{p}_T^{\text{miss}}$, object-corrected $\mathbf{p}_T^{\text{miss}}$, or $\mathbf{E}_T^{\text{miss}}$ and the selected lepton, with respect to the true $\mathbf{E}_T^{\text{miss}}$ and the number of reconstructed vertices in the event.	93
5.29	$\mathbf{p}_T^{\text{miss}}$ soft term systematic variations for $Z \rightarrow \mu\mu$ inclusive and 0 jet events.	95
5.30	$\mathbf{p}_T^{\text{miss}}$ total systematic variations for $Z \rightarrow \mu\mu$ inclusive and 0 jet events.	95
6.1	$\mathbf{E}_{T,\text{rel}}^{\text{miss}}$ and object-corrected $\mathbf{p}_T^{\text{miss}}$ distributions used for event preselection in the $H \rightarrow WW \leq 1$ jet same-flavour, and 0 and 1 jet different-flavour categories.	99
6.2	Resolutions of the $\mathbf{E}_T^{\text{miss}}$ and object-corrected $\mathbf{p}_T^{\text{miss}}$, and the $\mathbf{m}_T$ calculated using the $\mathbf{E}_T^{\text{miss}}$ or object-corrected $\mathbf{p}_T^{\text{miss}}$ for the ggF $H \rightarrow WW$ signal Monte Carlo sample in the 0 jet category, and post-fit combined $\mathbf{m}_T$ distributions for the 0 and 1 jet channels (both same and different-flavour analyses).	100
6.3	$\mathbf{p}_T^{\text{miss}}$ distributions in ggH and ZH events, where the Higgs decays to two high $\mathbf{p}_T$ photons which are included in the $\mathbf{p}_T^{\text{miss}}$	102
6.4	$\Delta\phi$ distributions between the $\mathbf{E}_T^{\text{miss}}$ and $\mathbf{p}_T^{\text{miss}}$ in ggH and ZH diphoton events.	103
B.1	Jet multiplicity distributions in $Z \rightarrow \mu\mu$ events for AlpgenJimmy and PowhegPythia.	118
B.2	Jet $\mathbf{p}_T$ and η distributions in $Z \rightarrow \mu\mu$ events for AlpgenJimmy and PowhegPythia.	119
B.3	Nominal $\mathbf{p}_T^{\text{miss}}$ 0, 1, and 2 jet distributions in $Z \rightarrow \mu\mu$ events for AlpgenJimmy and PowhegPythia.	121
B.4	Object-corrected $\mathbf{p}_T^{\text{miss}}$ 0, 1, and 2 jet distributions in $Z \rightarrow \mu\mu$ events for AlpgenJimmy and PowhegPythia.	122
B.5	Nominal $\mathbf{p}_T^{\text{miss}}$, object-corrected $\mathbf{p}_T^{\text{miss}}$, and $\mathbf{E}_T^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$ events for AlpgenJimmy and PowhegPythia.	123
B.6	Nominal Σp_T , object-corrected Σp_T , and ΣE_T distributions in $Z \rightarrow \mu\mu$ events for AlpgenJimmy and PowhegPythia.	124
B.7	Soft term modelling in the $\mathbf{p}_T^{\text{miss}}$, for AlpgenJimmy and PowhegPythia.	125
B.8	Jet term modelling in the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$, for AlpgenJimmy and PowhegPythia.	126

B.9 Muon term modelling in the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$, for AlpgenJimmy and PowhegPythia.	127
B.10 Electron term modelling in the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$, for AlpgenJimmy and PowhegPythia.	128

Preface

Many many years ago, there were no stars in the sky. Night was a dark velvet blanket that was pulled over the earth in the evening, to shield it from the hot African sun. To combat the darkness, the Bushmen tribes of Africa would build huge bonfires, and group around them in the evenings, to keep warm and trade stories of their hunts during the day. The children of the tribe were in charge of collecting the wood for the fire. On one particularly cold night, a little girl was in charge. She built the fire high, adding more and more wood until the flames danced and the sparks flew up, seeming to stick in the sky. Curious, she grabbed a handful of embers and roasting roots from the fire, and threw them up, up high, where the red and white roots now glow as red and white stars, and the ashes make a beautiful road between them. “And there the road is to this day. Some people call it the Milky Way, some call it the Stars’ Road, but no matter what you call it, it is the path made by a young girl many many years ago, who threw the bright sparks of her fire up into the sky to make a path in the darkness.”¹

There are many other stories of the sky, spanning the various people of earth throughout the ages. Of course, today we know much more about the true history of the universe, itself a tale of fire and force that is no less beautiful for being based on scientific fact rather than folklore. But no matter our culture, no matter where we were born, or whether we live today or thousands of years ago, three questions unite the human race: Who are we? Where did we come from? Where are we going to end up? I believe that these questions burn in all our hearts, driving us in our own ways to live our lives to the fullest capacity no matter which path each of us choose in life. And for some people,

¹Personal interpretation of /Xam Bushman star lore, including excerpt from Leslau, Charlotte and Wolf’s “African Folk Tales” (1963).

myself included, answering these questions at the most fundamental level has become the path of our choosing.

Particle physics is the study of the relationships between everything that makes up the universe, just one particular way we have of trying to figure out the answers to those three questions. It is the study of the smallest constituents of matter, and how the individual pieces fit together like the pieces of a puzzle to create the universe we see today.

As we have probed deeper and deeper into the mysteries of the universe, our experiments have grown bigger and bigger. What started with the ancient Greek philosophers as discussions requiring nothing more than our imaginations, slowly grew to quantitative observations of the world around us, and then to experiments that could be done on a table top. We learnt that we see objects because of the visible light that bounces off them, and we discovered that we could see the internal structure of objects by using light of higher energies (like x-rays). The higher the energy, the deeper we could see. Around the turn of the 20th century we tried helium ions in place of the light, and discovered the structure of an atom: protons and neutrons bound in a tight core, with a cloud of electrons orbiting at a distance around them. Fast forward 50 years and we were using high energy electrons in our experiments, learning that the proton itself is made up of smaller particles called quarks, held together by gluons. And today, we use the Large Hadron Collider at CERN - accelerating protons to the highest energies ever achieved - to effectively smash those quarks and gluons together, creating new particles that were never seen before.

Energy is the currency of the universe. And creating particles from high energy collisions is just like buying lunch at a very interesting restaurant. We have a menu that tells us which types of particles we can choose, and how much energy each particle costs. We can order whichever particle or groups of particles we like, as long as we have enough energy to pay for them. And of course, the more exotic the particle, the more energy it will cost. Each time we make a collision at the LHC, we go to the restaurant, and buy a new set of particles for the energy of our two protons.

But our particle physics restaurant has an important difference compared to a normal restaurant. We're allowed to choose particles such as protons (or neutrons) just about every time we go for

lunch. But certain particles - like our newly discovered Higgs boson - are found far more rarely on the menu. We are only allowed to choose a Higgs one in a billion times! That's a lot of lunches!

And that's why we need machines like the LHC, at laboratories such as CERN, the only place in the entire world where it is possible to go to our Particle Physics restaurant millions of times a second. The only place on the planet where we have enough energy to buy a Higgs for lunch. The only place on earth where ten thousand scientists from more than a hundred different countries have come together, bringing their expertise and passion for knowledge to solve some of the universes most fundamental questions.

We can't see the particles created in our collisions with our own eyes - they are far too small. Instead, we've built huge detectors around the collision point - amazing feats of engineering that act as extremely precise digital cameras, taking thousands of snapshots per second in the hope of catching a rare event, like the creation of a Higgs boson. The detectors themselves are gigantic 3-dimensional puzzles made up of a number of smaller subsystems, each developed with a specific task in mind, built by hundreds of people from around the world, and designed to give us a particular piece of information about the particles we have created. On its own, the information is interesting, and can tell us a bit about the particles as well as how well our detector is performing. But the real beauty is when we piece together the information from all the different components; only when our whole experiment is working in harmony are we able to extract the full set of information about the event. And from that we can say, "Higgs!"

It takes a large number of people working together for our experiments to succeed. From the engineers who built the accelerators and detectors, the people on shift making sure everything runs smoothly and safely, to the physicists inferring results from the collected data, our science is too big for any one individual, too big for one country - indeed, too big for any one continent!

I have met the most incredible people working at CERN, all of whom excel in science as well as in their own unique ways. And though we've come from many different backgrounds, with different creeds, colours and nationalities, we all share a common goal: a quest for knowledge that supersedes all borders between us. And this is the heart of CERN - a family that is as diverse as it is numerous. An organisation that unites nations in a quest for scientific advancement. You see, the

story of science is not cold and heartless. It is a story of adventure and intrigue, collaboration, hope and hard work, and we sit here at the culmination of thousands of years of exploration and discovery wondering, “What will be next?”

We are all scientists in our own way, you and I, driven to answer the three questions that unite us all: Where *did* we come from? Where *are* we going to end up? *Who are we?*

Well, we are individuals, contributing our own knowledge and skills for the completeness of our own lives. We come from our own countries, each with its own beautiful culture. But we are all part of one earth.

So tonight, go outside and look up at the sky. Admire the shining stars, each beautiful on its own. And then see the sky as a whole, how the individual stars combine to form the Milky Way galaxy: a little girl’s path home; our home in the universe. And see that although we may just be individual pieces on our own, if we work together, we can take on the universe.

Claire A. Lee

speech given at the CERN 60th Anniversary “Science for Peace” Celebration

UNESCO Headquarters, Paris, 1 July 2014.

Chapter 1

Introduction

Straddling the Franco-Swiss border in the countryside west of Geneva lies the European Organisation for Nuclear Research (CERN). Founded 60 years ago in 1954, CERN was established as a central site to develop an international laboratory for fundamental physics research that would bring nations together with a common goal: science. The history of CERN details many remarkable achievements where the boundaries of scientific research have been pushed time and again to provide answers to some of nature's most fundamental questions: revolutionising particle detection methods with the multiwire proportional chamber, the principles of which are still used for tracking in our detectors today; the discovery of the W and Z bosons - proponents of the weak force - in 1983; the startup of the Large Hadron Collider (LHC) in 2008, the world's highest energy particle accelerator; and, of course, the subsequent discovery of the Higgs-like boson in 2012. Today CERN is run by 21 member states, though many other countries from around the world (including South Africa and Taiwan) participate in its widespread research programme.

At an average depth of 100 m underground, the LHC is the final step in a successive chain of accelerators, designed to take protons to energies of 7 TeV per beam [1]. The LHC itself is a 27 km circumference ring of superconducting electromagnets interspersed with radiofrequency cavities that simultaneously accelerate two counter-rotating beams of protons arranged in bunches. At four points around the ring the beams are designed to cross, with triplet components before each designated

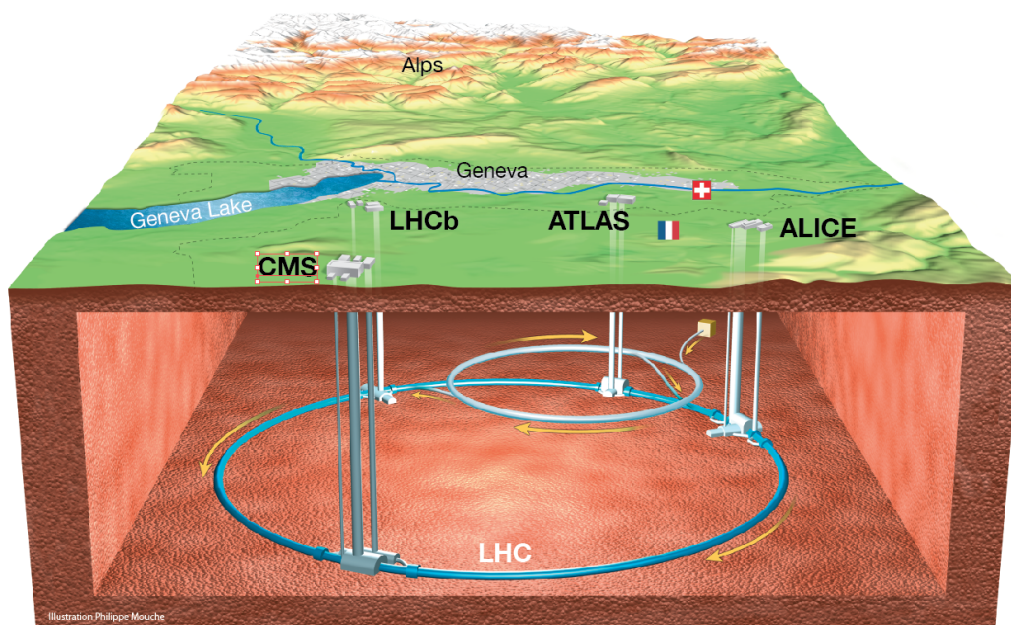


Figure 1.1: Overall view of CERN and the LHC. © CERN

interaction point providing final focusing of the beam in order to increase the chances of collision between the protons. At each of these points one of the LHC's four large, independent particle detectors are situated: ATLAS [2], ALICE [3], CMS [4], and LHCb [5]. ALICE and LHCb are specialised detectors, designed to study the properties of the quark-gluon plasma, and CP violation with B-meson physics respectively, while ATLAS and CMS are general-purpose detectors, with a broad range of experimental goals covering precision Standard Model measurements as well as searches for the Higgs boson and new physics processes.

The ATLAS experiment is a complex system of particle detectors and magnets built to extract as much information as possible from each event at the LHC. Individual subdetector systems are specially designed to detect the final-state particles originating from the collisions, particularly electrons, muons, photons and hadrons. The offline (and online) software algorithms combine the information from the various subdetector systems to provide good reconstruction of these individual particles, as well as more complex objects such as jets of particles from the hadronisation of quarks, and candidates for hadronically decaying taus. Finally, the large solid angle coverage of the detector

allows one to make a good measurement of the missing transverse momentum of the event via conservation of momentum.

In high energy hadron colliders the internal structure of the proton becomes important as the scattering proceeds between the quarks and gluons that make up the colliding protons. Since the internal momenta of the individual quarks and gluons within the proton is not known, a complete measurement of the energy of the event is not possible. However, the energy of the beam provides the proton energy in the longitudinal (z) direction which is highly boosted relative to any momentum in the xy plane, so the transverse momentum of the partons is approximately zero in comparison. Therefore any resultant momentum in the transverse direction after the event reconstruction would indicate missing transverse energy from the proton-proton scattering.

The missing transverse energy, $\mathbf{E}_T^{\text{miss}}$, is therefore defined as the magnitude of the momentum imbalance in the plane transverse to the beam axis, and can be obtained from the negative vector sum of the momenta of all the particles detected in a proton-proton collision. Assuming a complete solid angle coverage and perfect detector efficiency, the $\mathbf{E}_T^{\text{miss}}$ would signal the presence of non-interacting particles such as neutrinos or new weakly interacting particles. In practice, the detector phase space, reconstruction efficiencies and precision, as well as the presence of additional scattering interactions in the event, all have an important effect on the measurement.

A precise measurement of the $\mathbf{E}_T^{\text{miss}}$ is essential for many physics studies at the LHC, such as Higgs boson searches and measurements (like the $H \rightarrow b\bar{b}$ event shown in figure 1.2), as well as searches for new physics, like supersymmetric particles or extra dimensions. The primary detectors used for the measurement of the $\mathbf{E}_T^{\text{miss}}$ in ATLAS are the calorimeters, which are designed to provide excellent energy resolution at the LHC scale. An optimised reconstruction and calibration procedure was developed by the collaboration for use during the LHC Run 1. However, several effects (which will be discussed in detail in chapter 4) can affect this measurement leading to a large fake $\mathbf{E}_T^{\text{miss}}$ signature or degraded resolution, and so a quasi-independent and complementary measurement of the $\mathbf{E}_T^{\text{miss}}$ was developed as an additional aid for reducing backgrounds and calculating $\mathbf{E}_T^{\text{miss}}$ scale-based quantities such as transverse mass. This thesis covers the development of this method, which instead focuses on using charged particle tracks from the ATLAS Inner Detector to calculate the

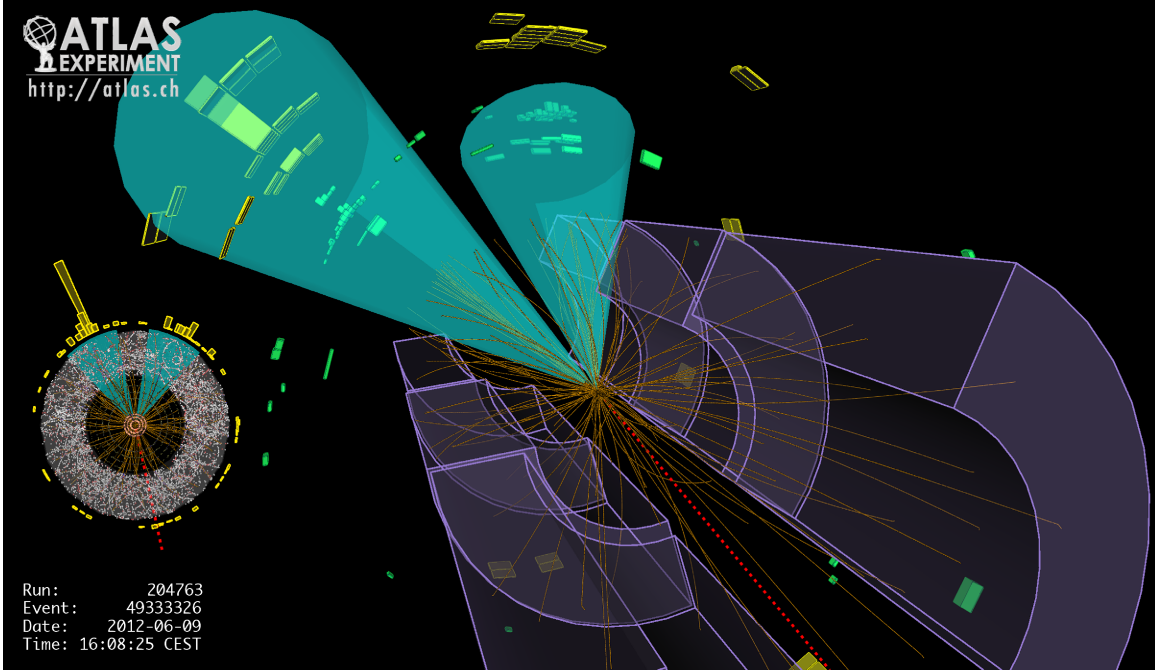


Figure 1.2: Display of a Higgs boson candidate event in the $b\bar{b}$ channel with zero selected leptons. The event contains two identified b-jets with transverse momenta of 193 GeV and 78 GeV, respectively, with an invariant mass of 123 GeV. The missing energy in the transverse plane is 271 GeV. [6]

track-based missing transverse momentum - denoted $\mathbf{p}_T^{\text{miss}}$ - and also details the performance and some physics-use cases of $\mathbf{p}_T^{\text{miss}}$ within ATLAS.

In chapter 2 we start with overview of the Standard Model of Particle Physics, covering in detail the theory of proton-proton interactions at hadron colliders as well as vector boson production and their decays. This is followed by a short introduction to the Large Hadron Collider and the ATLAS experiment in chapter 3, where our experiment is introduced for readers unfamiliar with CERN. In chapter 4 we introduce the concept of and motivation for the track-based missing transverse momentum and describe its reconstruction, and in chapter 5 we investigate in detail the performance of the $\mathbf{p}_T^{\text{miss}}$ in events with vector bosons and jets. In chapter 6 we consider the use of $\mathbf{p}_T^{\text{miss}}$ in current physics analyses, and take a look towards further developments that will play a crucial role in the future. Finally we close with a conclusion and outlook on what we can expect as we draw closer to the restart of the LHC for it's higher energy run 2.

The tasks performed during the course of my doctoral studies on ATLAS have been numerous and diverse, and have all contributed to a broader understanding of the experiment and its multiple

facets. Prior to moving to CERN I worked on simulations of the cavern background in the Muon Spectrometer system, as well as some initial Monte Carlo studies on Higgs decays via a hidden sector. Once based at CERN, to qualify as an ATLAS author I performed operations work on the Liquid Argon (LAr) Calorimeter system, first training with shifts in the ATLAS control room during data taking, then becoming what was called a “supershifter”, acting as an intermediary between the shifters in the control room and the experts behind the scenes. I spent the next year as an on-call expert for the LAr online system, with week-long, 24 hour per day shifts responsible for the daily optimal running and emergency troubleshooting of the software system and readout computers. I also co-organised a LAr online and software system training workshop, and personally trained two new online on-call experts to work with us. I also believe that outreach is important, and I trained as an ATLAS underground guide, hosting many public and semi-VIP visits underground to the ATLAS detector during shutdown, as well as speaking to students from South Africa, Edinburgh and Algeria during ATLAS Virtual Visits.

The $\mathbf{p}_T^{\text{miss}}$ studies detailed in this thesis were my main focus, and when I arrived at CERN and began a collaboration with the Academia Sinica group my first project was to reconstruct the $\mathbf{p}_T^{\text{miss}}$ on the 2011 7 TeV data (an initial study had been done by the Sinica group on the first 900 GeV data from ATLAS). Our results were presented during many internal group meetings, and even then we saw the advantages of our method in contrast to the traditional calorimeter-based measurement. The rest of the year was spent validating the lepton, primary vertex, and general track selections for the calculation, and comparing the nominal results to new proposals from the tracking group. It was in 2012 with the increased beam energy and collision backgrounds that the method really gained momentum. The $H \rightarrow WW$ group incorporated the $\mathbf{p}_T^{\text{miss}}$ first, and I was in charge of integrating the $\mathbf{p}_T^{\text{miss}}$ development code into the official $H \rightarrow WW$ analysis framework. Later on we started to explore additional possibilities, such as including photons, and I worked with experts from the $H \rightarrow \gamma\gamma$ group to provide a $\mathbf{p}_T^{\text{miss}}$ measurement for their analysis.

At this point the $\mathbf{p}_T^{\text{miss}}$ was still generally a tracks-only measurement, meaning that only the momentum of charged particle tracks measured by the ATLAS Inner Detector was taken into account, and therefore a significant fraction of the event momentum was lost due to neutral particles in jets. I embarked on an effort to quantify the effect of this loss on the performance of the $\mathbf{p}_T^{\text{miss}}$, which led to the development of the object-corrected version. Here the full calorimetric measurement of the jet

momentum is used in place of the jet tracks, as we noticed that we gained significant performance improvements with this method (though a full study on the various jet selection possibilities needed to be performed as the recommendations used for the $\mathbf{E}_T^{\text{miss}}$ calculation were too loose and made our algorithm vulnerable to non-signal backgrounds).¹ The consolidation of the $\mathbf{p}_T^{\text{miss}}$ into the nominal (tracks-only) and object-corrected versions was then finalised on the full set of 8 TeV data from 2012, and the full set of performance studies completed. These are the results that are presented in this thesis, and results and figures included that were not produced directly by me are referenced. Finally, as of today, both versions of the $\mathbf{p}_T^{\text{miss}}$ are maintained (and are now integrated into the ATLAS reconstruction software) as each has its own advantages depending on desired use and event topology.

¹The full reconstructed electron momentum using the calorimeter and Inner Detector was already in place for the $H \rightarrow WW$ analysis. The muon combined $\mathbf{p}_T$ (from the Muon Spectrometer and Inner Detector) was also added for completeness.

Chapter 2

Theory of Physics at the LHC

2.1 The Standard Model of Particle Physics

Since the Greek philosophers Leucippus and Democritus first coined the term “atomos” - meaning “indivisible” - to refer to the smallest pieces into which matter could be partitioned, science has been on a quest to discover the fundamental building blocks of matter. Based on the work of thousands of physicists from around the world (with notable pioneers) the current understanding culminated in what is known as the Standard Model (SM), an effective¹ quantum field theory that has proved remarkably² successful in explaining existing results as well as in predicting new ones for the past four decades [7].

Particle physics is the study of the elementary constituents of the universe, quantisations of their representative fields that can be contained in two classes: spin-1/2 fermions which describe matter, and integer-spin bosons describing the interactions. All particles have corresponding antiparticles (except for the neutral bosons which are themselves their own antiparticle). The bosons can be divided into two groups: the massive scalar Higgs boson, and the spin-1 gauge bosons which mediate

¹An effective theory is one that is valid for a given domain, such as an energy scale. The SM is incomplete as it doesn’t address issues such as gravity, dark matter, or grand unification. However at the the current available energy scale the SM has passed all tests (such as precision electroweak and flavour measurements) with flying colours.

²Annoyingly!

the fundamental forces between particles. The electromagnetic (EM) force is mediated by the massless, electrically-neutral photon, providing an infinitely-ranged interaction. The gluon is also massless, though unlike the photon it has non-zero colour charge which allows for self interactions that effectively confine the range of the strong interaction to 10^{-15} m. Finally, the (electrically) charged W and neutral Z bosons are massive and therefore short-lived, imposing a finite range for the weak interaction.

The fermions are also further classified according to their charges (which influence the way they interact), and all fermions carry flavour charge and hence interact via the weak force. The subset of quarks also has colour and electric charge, allowing strong and electromagnetic interactions respectively. Of the leptons, only the electron, muon, and tau lepton carry electric charge, while the neutrinos are neutral. Finally, in addition to the categorisations mentioned above, the fermions are split into three generations, where each generation is an increasingly massive duplicate of the previous one. Figure 2.1 shows a graphical representation of the total set of fundamental particles we currently know of, and their properties.

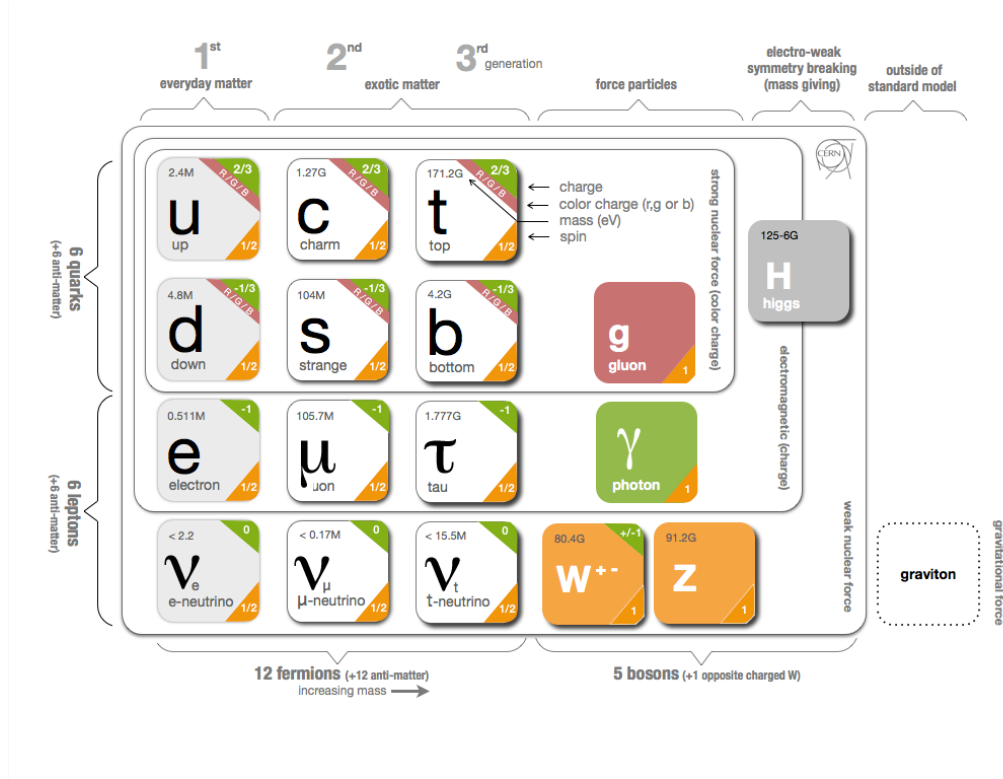


Figure 2.1: The set of fundamental particles comprising the Standard Model today. © CERN

The various types of interactions originate from very different sectors of particle physics, and the field theories representing each of these sectors were developed separately over a number of decades (appendix A contains a more detailed account of the theories of quantum electrodynamics, quantum chromodynamics, and electroweak unification). The core of what we currently know as the Standard Model of particle physics (SM) came from the unification of the electromagnetic and weak interactions, with the addition of the Higgs mechanism that provides the massive vector bosons with their mass; this, convoluted with the field theory of quantum chromodynamics, provides us with the framework we have for describing particle interactions today.

The Standard Model therefore combines the dynamics of the bosons and fermions into a local $SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge symmetry invariant under special relativity, where C represents colour charge, W weak isospin, and Y hypercharge. Together these are described by the SM Lagrangian density formulated with fermion fields and the Electroweak (EW), Quantum Chromodynamic (QCD), and Higgs sectors:

$$\begin{aligned}
\mathcal{L} = & -\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}^\alpha G_{\alpha}^{\mu\nu} & \left\{ \begin{array}{l} W^\pm, Z, \gamma \text{ and} \\ \text{gluon kinetic energies} \\ \text{and self-interactions} \end{array} \right. \\
& + \bar{L}\gamma^\mu \left(i\partial_\mu - \frac{1}{2}g\tau_i W_\mu^i - g'\frac{Y}{2}B_\mu \right) L + \bar{R}\gamma^\mu \left(i\partial_\mu - g'\frac{Y}{2}B_\mu \right) R & \left\{ \begin{array}{l} \text{Lepton and quark kinetic en-} \\ \text{ergies, and their interactions} \\ \text{with } W^\pm, Z \text{ and } \gamma \end{array} \right. \\
& + g_s (\bar{q}\gamma^\mu T_\alpha q) G_\mu^\alpha & \left\{ \begin{array}{l} \text{Interactions of quarks with} \\ \text{gluons} \end{array} \right. \\
& + \left| \left(i\partial_\mu - \frac{1}{2}g\tau_i W_\mu^i - g'\frac{Y}{2}B_\mu \right) \Phi \right|^2 V(\Phi) & \left\{ \begin{array}{l} W^\pm, Z \text{ and } \gamma \text{ masses and cou-} \\ \text{pling to the Higgs boson} \end{array} \right. \\
& - (G_1 \bar{L}\Phi R + G_2 \bar{L}\Phi^c R) + \text{hermitian conjugates} & \left\{ \begin{array}{l} \text{Lepton and quark masses and} \\ \text{coupling to the Higgs boson} \end{array} \right.
\end{aligned} \tag{2.1}$$

$W_{\mu\nu}$ and $B_{\mu\nu}$ describe the spin-1 vector fields from the electroweak unification, with coupling strengths g and g' respectively. The W fields form an isotriplet required to maintain the SU(2) gauge invariance, while B is the single field required by U(1). For the QCD sector, $G_{\mu\nu}^\alpha$ are the gluon gauge fields with couplings g_s , where $\alpha = 1, \dots, 8$ for SU(3) invariance.

Y and τ_i are the generators of U(1) and SU(2) transformations respectively. Left- (L) and right-handed (R) fermions behave differently under the EW transformations, and as such are contained in different multiplets: the left-handed leptons and neutrinos form an SU(2) doublet ($\begin{smallmatrix} \nu_L \\ \ell_L \end{smallmatrix}$), while the right-handed lepton ℓ_R is a singlet (since in the framework of the Standard Model no right-handed neutrinos exist). This leads to parity violation as only the left-handed components of particles participate in the weak interaction: the term $\tau_i W_\mu^i$ - a 2×2 matrix - gives zero when acting on the right-handed singlet. Unlike Y and τ_i , the eight SU(3) generators T_α are not all diagonal, allowing the colour of a quark to change during an interaction with a gluon.

Particle masses arise from their coupling to the Higgs field Φ , a complex SU(2) doublet (in the SM framework) with four real components:

$$\Phi = \begin{pmatrix} \Phi_1 + i\Phi_2 \\ \Phi_3 + i\Phi_4 \end{pmatrix} \quad (2.2)$$

The scalar Higgs potential is given by

$$V(\Phi) = \mu^2 \Phi^* \Phi + \lambda |\Phi^* \Phi|^2 \quad (2.3)$$

where μ^2 has units of mass² and λ is the dimensionless Higgs quartic coupling constant. The coefficient $\mu^2 < 0$ implies that the potential has a minimum not at zero but at $v = \sqrt{\frac{-\mu^2}{\lambda}}$, which spontaneously breaks the EW symmetry, mixing the four Goldstone bosons arising from the Higgs field with the longitudinal components of W_μ^i and B_μ in the process. A gauge transformation exploiting the local symmetry takes us to the unitary gauge where $\Phi_1 = \Phi_2 = \Phi_4 = 0$. Thus the Higgs vacuum expectation value (vev) is given by

$$\langle V(\Phi) \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.4)$$

with a value of 246 GeV (determined experimentally via the measurement of the W mass), and we are left with just one real scalar H , the physical Higgs field we have today:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad (2.5)$$

In this gauge we obtain the massive charged W^+ and W^- bosons from the first two isospin gauge bosons. The third isospin component mixes with B_μ to form the mass eigenstates

$$Z_\mu = -B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W \quad (2.6)$$

$$A_\mu = B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W \quad (2.7)$$

where θ_W is the weak mixing angle. The first equation gives us the massive Z boson, and the masses of the Ws and Z are related by $\frac{M_W}{M_Z} = \cos \theta_W$. The interaction of the field with the A_μ mixture preserves the $U(1)_{EM}$ symmetry, and so the resulting gauge boson - the photon - remains massless.

The final term in the SM Lagrangian covers the mass terms for the fermions, which, unlike the gauge bosons above, are generated through the particles' Yukawa couplings to the Higgs doublet. In the Lagrangian above, G_1 and G_2 are the couplings for leptons and quarks respectively, and are proportional to the masses of the fermions. For the leptons, the choice of Φ above allows the Higgs mechanism to interact only with the charged leptons, generating a Dirac mass for them but excluding the neutrinos from the interaction. The quarks form an $SU(2)$ left doublet and two right singlets: $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$, u_R , d_R , so the down-type quarks use a mechanism similar to that for the leptons to obtain their mass. For the up-type quarks this obviously does not work, so defining

$$\Phi^c = \varepsilon_{ij} \Phi^{j*} \quad (2.8)$$

also leads to an invariant term for the Yukawa interaction, but one which acts on the up-type quarks. The fermion masses are therefore given by

$$m_{\ell,u,d} = \frac{1}{\sqrt{2}} G_{\ell,u,d} v \quad (2.9)$$

where the mass of each particle depends on the strength of the coupling between it and the Higgs field.

2.2 Physics at Hadron Colliders

Physics at colliders such as the LHC is a contest of energy scales. Although bunches of protons make up the beam, at the high energies available we can probe extremely small distance scales, so the actual interactions are between the constituent partons (quarks and gluons), not the protons themselves. These interactions can be classified as either hard or soft, and the experimental signatures and understanding of each are significantly different in the two cases. Furthermore, the final state particles from the interaction (and subsequent decays) we observe in our detector are the leptons and composite hadrons that are stable at large distances, and, thanks to processes like hadronisation (see appendix A), lead to messy experimental signatures that make it difficult to extract basic information about the original collision. In the following, a knowledge of the relativistic kinematics of collider experiments is assumed; for a review of this and a description of the particular variables involved in collider experiments, see, for example, section 46 (page 508) of [8] and appendix A of [9].

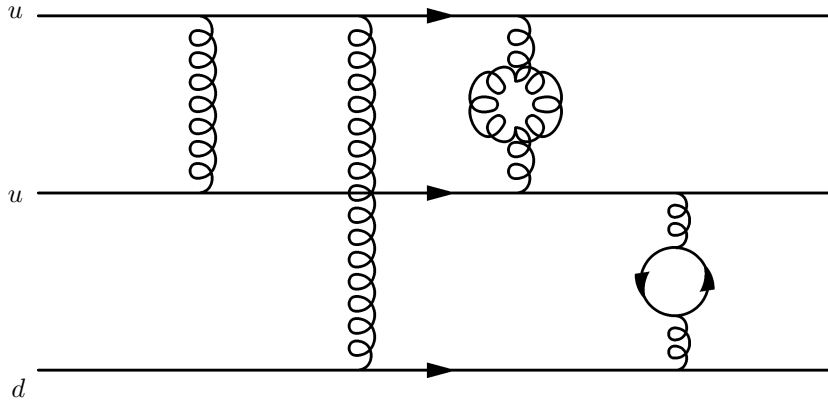


Figure 2.2: Schematic illustration of a proton, consisting of three valence quarks (uud) bound by gluons. The gluon self interaction and sea quark loops are also shown.

The proton - like all hadrons - is a dynamically bound system of interacting quarks, gluons, and virtual quark-antiquark pairs known as sea quarks, illustrated in figure 2.2. Interactions between partons from colliding protons can be parameterised by Q^2 , the negative of the four-momentum transfer ($Q^2 = -q^2$). The four-momentum transfer is the square of the change in the four vector of either parton during the interaction (also known as the Mandelstam t variable):

$$q^2 = (p_1 - p_3)^2 = (p_2 - p_4)^2 \quad (2.10)$$

For low values of Q^2 the proton can be modelled as a bound system of the three valence quarks to good approximation, but at high Q^2 (such as the LO resonant scattering $q\bar{q} \rightarrow V$), the contributions of the gluons and sea quarks to the overall properties of the proton become significant.³

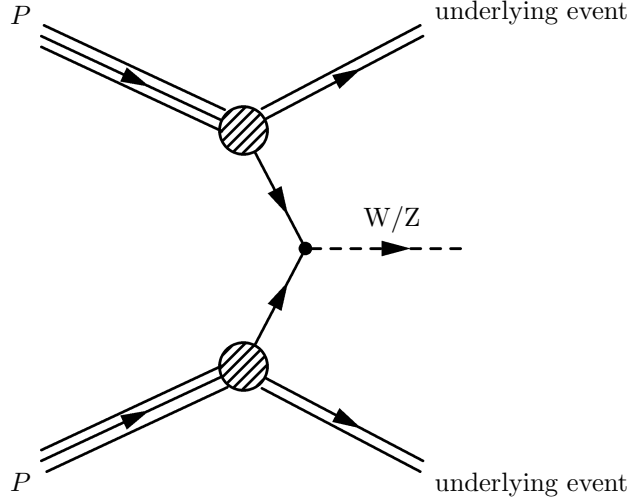


Figure 2.3: Schematic illustration of a proton-proton interaction showing the production of a vector boson and the resulting underlying event contribution.

When two protons collide at the LHC, the hard interaction normally occurs between a single parton from each proton; this is shown for the case of W or Z boson production in figure 2.3. Accompanying the hard interaction is what is known as the underlying event: the soft processes accompanying the hard scattering due to additional interacting quarks or gluons within the same two protons, which includes processes such as diffraction, multiple parton interactions, as well as soft initial- and final-state radiation (ISR and FSR). To fully understand the total proton-proton (pp) interaction,

³For example, only about half of, e.g., the proton's total momentum comes from all the quarks (including anti-quarks) - the other half of the nucleon momentum is carried by the gluons.

knowledge of the composition of the quarks, gluons and sea quarks within the proton, as well as their individual momentum contributions at each parton-parton interaction vertex, is essential.

2.2.1 Parton distributions within the proton

The proton structure functions parametrise the interaction at the parton-parton vertex, and are functions $F_n(x, Q^2)$ of Q^2 , and the fraction of the momentum of the proton carried by the individual parton (also known as the scaling variable):

$$x = \frac{p_i}{\sqrt{s}/2} \quad (2.11)$$

These structure functions can be written as a sum over the parton distribution functions (PDFs) $f_i(x, Q^2)$, for example:

$$F_2(x, Q^2) = \sum_i e_i^2 f_i(x, Q^2) x \quad (2.12)$$

Here e is the electric charge on the i th parton and the sum extends over all parton types (gluons and quark flavours $u, d, s, \dots$). The PDF can thus be interpreted as the probability⁴ of finding a parton of type i and momentum fraction x inside the proton.

A precise knowledge of the PDFs is essential for analyses based on QCD, as well as for those based on Beyond the Standard Model-type physics at hadron colliders such as the LHC. The probability for a given process X to occur in any collision is given by its cross section σ , calculated by convoluting the PDFs with the parton-level cross section $\hat{\sigma}$:

$$\sigma(P_1 P_2 \rightarrow X) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(ij \rightarrow X; x_1 P_1, x_2 P_2, Q^2) \quad (2.13)$$

where $f_{i,j}$ are the parton distribution functions for partons i and j , and $x_{1,2}$ are the momentum fractions of partons i and j in protons P_1 and P_2 respectively. Unfortunately, the PDFs themselves are not predicted by the SM theory, and rely on a fit to data from various experiments⁵ using

⁴Strictly, a number density.

⁵DIS, HERA, fixed-target, Tevatron, and a few of the latest use LHC data too.

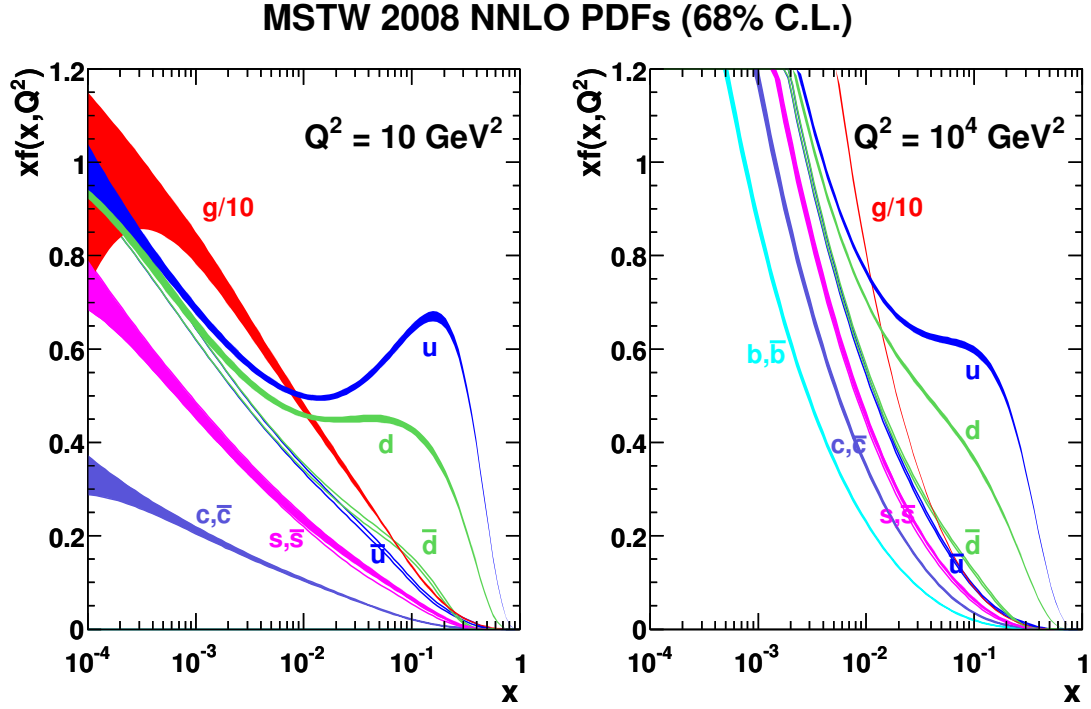


Figure 2.4: Parton Distribution Functions (PDFs) for gluons and quarks (excluding t and $\bar{t}$) at the LHC as a function of x , shown for $Q^2 = 10$ and 10^4 GeV^2 . Predictions are made at NLO with 68% confidence level by the MSTW PDF fitting group [10].

the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equation [11, 12, 13]. Figure 2.4 shows the PDFs for gluons and quarks (excluding t and $\bar{t}$) at the LHC, predicted to NLO by MSTW2008 [10]. The theoretical and ATLAS-measured cross sections for a variety of SM processes as well as the total proton-(anti)proton cross section are shown in figure 2.5.

2.2.2 W and Z physics at the LHC

The $W^\pm$ and Z^0 vector bosons were predicted by Glashow, Salam and Weinberg as a result of their electroweak unification theory. The first indirect hints of these particles came in 1973, when the Gargamelle bubble chamber at CERN observed evidence of weak neutral currents in photographs showing the tracks of electrons. But it was not for another 10 years until direct evidence of the W and Z bosons was announced by the UA1 and UA2 collaborations using CERN's Super Proton

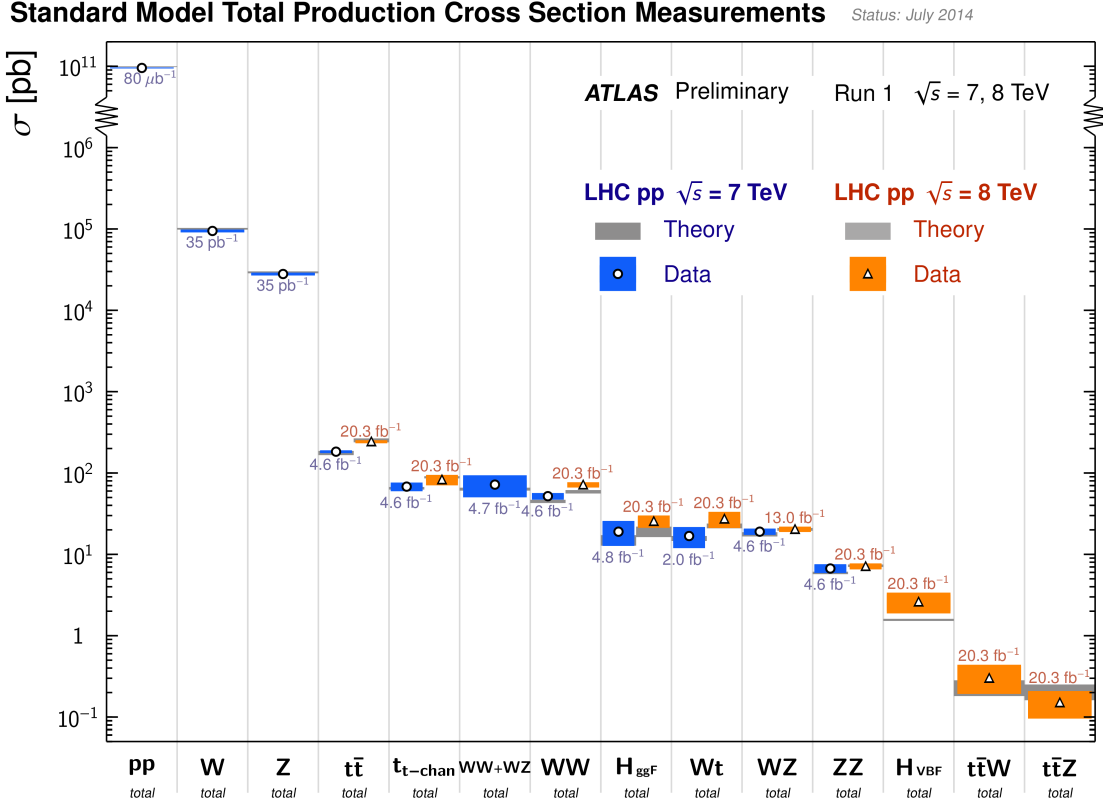


Figure 2.5: Standard Model production cross sections for a variety of processes at the LHC, showing both theoretical and measured values.

Synchrotron (SPS), which had just been converted from a single-beam accelerator into a double-beam proton-antiproton collider for exactly this purpose.

Since their discovery the W and Z bosons have been studied extensively using CERN's Large Electron-Positron collider (LEP) and Fermilab's Tevatron, and now, at the LHC, their relatively high production rate and easily identifiable experimental signatures allow us to use them as standard candles for various studies. The most precise current values for the masses and widths of the W and Z bosons are given below:

m_W	$80.385 \pm 0.015 \text{ GeV}$
Γ_W	$2.085 \pm 0.042 \text{ GeV}$
m_Z	$91.1876 \pm 0.0021 \text{ GeV}$
Γ_Z	$2.4952 \pm 0.0023 \text{ GeV}$

Table 2.1: Current most precise measurements of the mass and width of the W and Z bosons [8]

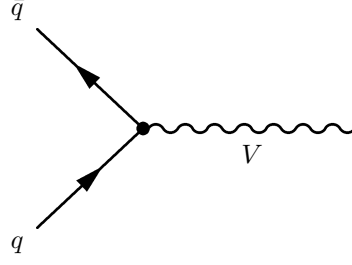


Figure 2.6: Leading order and dominant vector boson production through the tree-level Drell-Yan channel ($q\bar{q}$ annihilation).

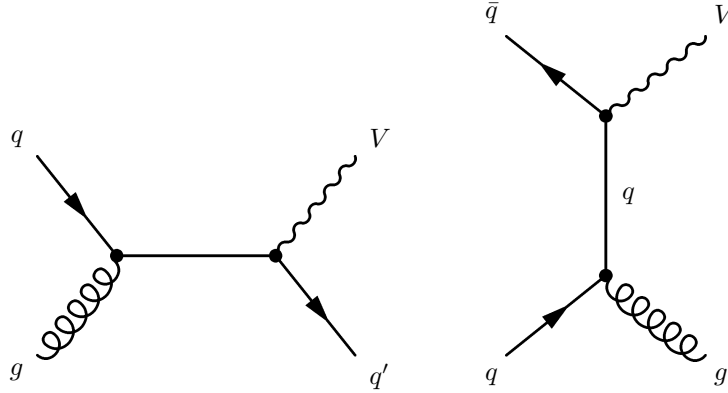


Figure 2.7: Next-to-leading order vector boson production processes in association with 1 jet. The second most dominant production process overall is the s -channel quark-gluon scattering (left). The t -channel Drell-Yan (right) processes is also shown.

2.2.2.1 Production mechanisms

The dominant W/Z boson production mechanism at the LHC is via the Drell-Yan process $q\bar{q} \rightarrow V$, which occurs about 65% of the time (figure 2.6). This rate covers contributions from both valence-sea and sea-sea quark interactions, and may also include initial-state gluon radiation at next-to-leading order. The next dominant production process (around 20%) results from quark-gluon scattering. Higher order corrections to the processes originate from loop corrections, or one or more hard radiated quarks or gluons in the final state which are reconstructed as jets in the detector (figure 2.7). Production of the W and Z bosons in association with jets is a large source of background for many physics processes at the LHC, both within the Standard Model and beyond. But the events themselves are interesting in their own right, as the jet production requires a quark-gluon vertex, allowing us to probe not only EW, but strong interactions as well. Any additional parton in the final state therefore adds another strong interaction vertex, so these events provide a good source

for improving our understanding of QCD to higher orders. A summary of the W/Z production processes up to NNLO is shown in table 2.2.

Order	W/Z production process	
LO	$q + \bar{q} \rightarrow V$	
NLO	$q + \bar{q} \rightarrow V$	(one-loop correction)
	$q + \bar{q} \rightarrow V + g$	
	$q(\bar{q}) + g \rightarrow V + q(\bar{q})$	
NNLO	$q + \bar{q} \rightarrow V$	(two-loop correction)
	$q + \bar{q} \rightarrow V + g$	(one-loop correction)
	$q + \bar{q} \rightarrow V + g + g$	
	$q(\bar{q}) + g \rightarrow V + q(\bar{q})$	(one-loop correction)
	$q(\bar{q}) + g \rightarrow V + q(\bar{q}) + g$	
	$q + \bar{q} \rightarrow V + q + \bar{q}$	
	$q(\bar{q}) + q(\bar{q}) \rightarrow V + q(\bar{q}) + q(\bar{q})$	
	$g + g \rightarrow V + q + \bar{q}$	

Table 2.2: Vector boson production processes at LO, NLO, and NNLO at the LHC.

The cross section for W/Z production is calculated from the sum of the amplitudes of all contributing initial states (such as those listed in table 2.2) which are affected by the PDFs of the protons at the given energy scale. Since the energy scale of the interaction is determined by the momenta of the incoming partons p_1 and p_2 , then for the case of LO resonant scattering $q\bar{q} \rightarrow V$,

$$(p_1 + p_2)^2 = (x_1 P_1 + x_2 P_2)^2 = M_V^2 \approx 10^4 \text{ GeV}^2 \quad (2.14)$$

where P_1 and P_2 are the momenta of the protons, and x_1 and x_2 the respective parton momentum fractions, typically between 10^{-3} and 10^{-1} for this process.⁶

A notable example of the dependence of the cross section on the PDFs is the asymmetry between W^+ and W^- production at the LHC (as it is a pp collider), mainly due to the higher probability of the valence u quarks in the PDF (see again figure 2.4). A breakdown of the quark flavour contributions to the LO W^+ and W^- boson production cross sections are shown as a function of $\sqrt{s}$ in figure 2.8 a). One can see that overall more W^+ bosons are produced, since they primarily depend on the $u(x)$ and $\bar{d}(x)$ distributions, while W^- production, which is dependent on the $\bar{u}(x)$ and $d(x)$

⁶As one can see from figure 2.4, the PDFs for the sea quarks become comparable to those of the valence quarks in this range, which is why the sea-sea interactions are also important at this scale.

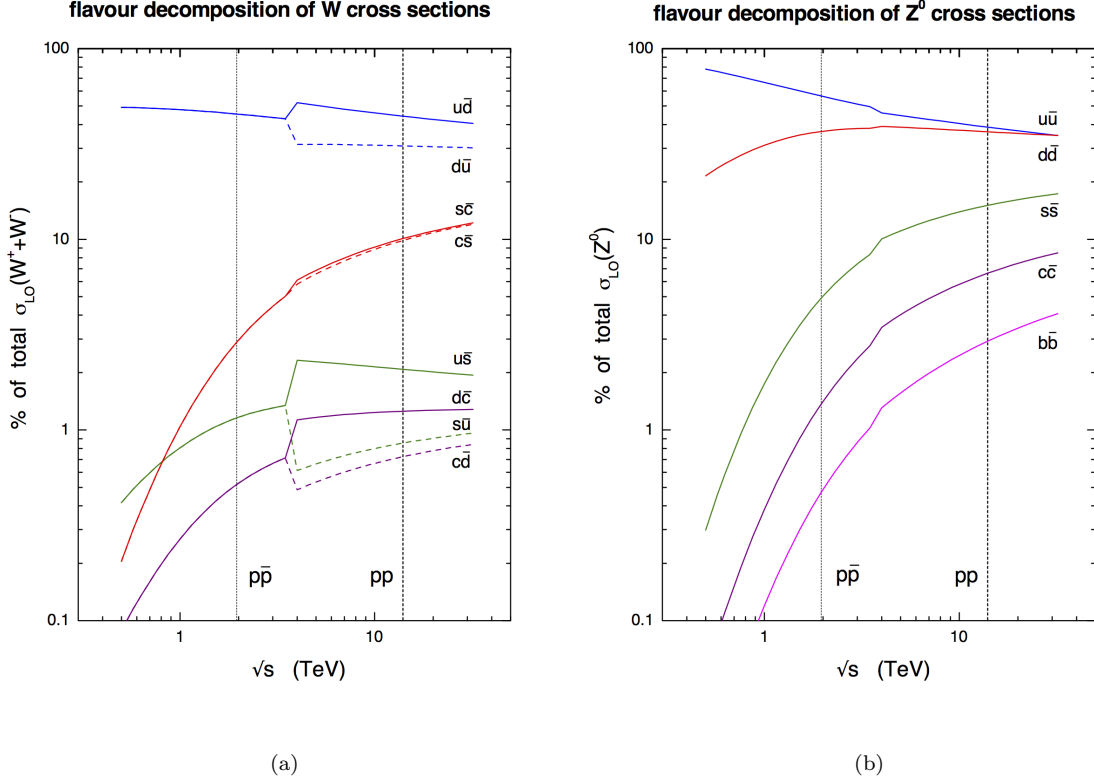


Figure 2.8: Individual quark subprocess contributions to the LO W boson (a) and Z boson (b) production cross sections as a function of $\sqrt{s}$ [10]. For the W boson (a), where the two lines split, the solid line indicates the W^- production, and the dashed line the W^+ . The discontinuity is due to the transition from $p\bar{p}$ to pp scattering as the calculations describe first the Tevatron and then the LHC predictions.

distributions, occurs at only about 70% of the W^+ rate.⁷ The corresponding flavour decomposition for Z boson production is shown in figure 2.8 b).

2.2.2.2 Decay channels

The W and Z vector bosons are massive particles with very limited lifetimes, so they decay almost instantaneously after production to the lighter, stable particles we observe in our detector. The decay can occur through a number of different channels, as long as the final state particles are lighter than the initial particle and all quantum numbers at the vertex are conserved. The total decay rate is

⁷ pp collisions have 2x more $u\bar{d}$ than $d\bar{u}$ collisions due to the valence quark content of the proton (uud). However, the sea-sea production is symmetric, and dilutes the W^+/W^- ratio from 2 to ≈ 1.4 .

calculated as the sum over all possible final states (similar to the production probability as the sum over all initial states). The probability of the decay occurring through a particular channel is given by its branching ratio, $\frac{\Gamma_i}{\Gamma}$, which is the fraction of the partial decay rate of that particular channel to the total decay rate of the boson.

The dominant decay modes of the W and Z bosons are into fermion-antifermion pairs, for all fermions except for the top quark. Of these, the primary decays are through hadronic channels which occur in threefold multiplicity due to the colour charge of the quarks (and the colour blindness of the vector bosons), contributing almost 70% to the total decay rate. However, this particular channel proves very challenging experimentally at hadron colliders because of the abundant production of jets from QCD background processes. The cleanest channels at the LHC and the primary modes of identification are therefore the decays to leptons.

To preserve charge, the W^- (W^+) must decay to a lepton (antilepton) and an antineutrino (neutrino), where the neutrino must be the same flavour as the lepton for lepton number conservation. The Z decays to lepton-antilepton pairs as well as to a neutrino-antineutrino pair. (Note that here and henceforth we use the experimental convention of denoting the electrically-charged electrons, muons, and tau particles as leptons, and considering the neutrinos separately.⁸) The various dominant decay modes of the W and Z bosons are summarised in table 2.3 along with their respective branching ratios [8]. While the bosons are similar in most respects, the fraction of Z bosons decaying into charged leptons is smaller than that of the W, due to the extra possibility of the Z decaying invisibly ($\nu\bar{\nu}$). Furthermore, the couplings between the gauge bosons and leptons are flavour independent⁹, which can be seen by the consistency (within error) of the branching ratios in the different charged lepton channels.

2.2.2.3 W and Z boson cross sections at the LHC

One of the measurable quantities obtained from an experiment is the number of events N_V observed for a particular process, a value that depends on the production cross section times the branching

⁸In the experimental sections we will further restrict “ ℓ ” to refer to only e or μ .

⁹This is called lepton universality and has been tested in a number of experiments worldwide, though recent results from LHCb may be pointing towards a first difference [14].

	Decay Mode	Measured Branching Ratio
W^+	hadrons	$67.60 \pm 0.27 \%$
	$e^+\nu_e$	$10.75 \pm 0.13 \%$
	$\mu^+\nu_\mu$	$10.57 \pm 0.15 \%$
	$\tau^+\nu_\tau$	$11.25 \pm 0.20 \%$
Z^0	hadrons	$69.91 \pm 0.06 \%$
	$\nu\bar{\nu}$	$20.00 \pm 0.06 \%$
	e^+e^-	$3.363 \pm 0.004 \%$
	$\mu^+\mu^-$	$3.366 \pm 0.007 \%$
	$\tau^+\tau^-$	$3.370 \pm 0.008 \%$

Table 2.3: Vector boson decay modes and measured branching ratios [8]. W^- modes are charge conjugates of the W^+ .

ratio of the studied process σ_V , the integrated luminosity provided by the accelerator $\mathcal{L}$, and the detector efficiency ϵ :

$$N_V = \sigma_V \epsilon \mathcal{L} \quad (2.15)$$

While the luminosity and detector efficiency are experimentally determined quantities, the cross section times branching ratio for the given process can be computed theoretically and compared with measured values. For the case of W or Z boson production with its subsequent leptonic decay, the predicted values are shown in table 2.4 below. The theoretical calculations are made to NNLO in perturbative QCD, and are limited by the uncertainties on the PDFs, higher order QCD processes, and electroweak radiative corrections (which are available only to NLO). The values are computed using the FEWZ program [15], and the MSTW2008 set of PDFs [10], and shown for a centre of mass energy of $\sqrt{s} = 8$ TeV.

$\sigma_{W^+ \rightarrow l\nu}^{NNLO}$	7.12 ± 0.20 nb
$\sigma_{W^- \rightarrow l\nu}^{NNLO}$	5.06 ± 0.13 nb
$\sigma_{W^\pm \rightarrow l\nu}^{NNLO}$	12.18 ± 0.32 nb
$\sigma_{Z^0 \rightarrow ll}^{NNLO}$	1.13 ± 0.04 nb

Table 2.4: Theoretical NNLO production cross sections times their respective leptonic decay branching ratios for W and Z bosons at $\sqrt{s} = 8$ TeV [15].

2.3 Monte Carlo Generators

The great benefit of experimental physics is its potential for discovery and the testing of current theoretical predictions, but neither is possible without a thorough understanding of all the physical processes involved in a particular measurement. Comparisons between theory and data require a method of translation between the theoretical predictions and the results we obtain in our detector. Where possible, some analyses use data-driven methods to estimate certain backgrounds, but for the most part simulated data are necessary. Monte Carlo (MC) generators provide us with this tool, allowing us to consider specific events as they would be seen by our experiment. This is crucial for the interpretation of our results, as well as their extrapolation to other phase spaces.

To accurately model the physics of the events, information is needed on a number of different processes: the structure of the hadrons (which depend on the PDFs), methods of parton showering and hadronisation, calculations involving the hard scatter interaction, initial and final state radiation, as well as soft processes formed from the underlying event and pileup. A number of generators are available that use different methods or approximations for the various steps involved in the modelling, and generally one chooses the generator that provides the best comparison to the data. A detailed review of the event generators used for LHC physics is given in [16].

There are various groups providing PDFs available for use in analysis: these mainly differ in the parametrisation of the PDFs, the treatment of heavy quarks, the treatment of the strong coupling constant α_s , and the treatment of errors. ATLAS primarily uses the CT10 PDFs at next-to-leading order (NLO) [17] for signal samples, and the MSTW08 leading order (LO) PDF [10] for the additional pileup interactions. For each, the ATLAS Collaboration developed its own tune [18, 19, 20] which varies the multiple parton interaction parameters to fit the data from ATLAS more closely (since multiple parton interactions are more probable for hard events than for soft ones).

The PDFs are the main source of theoretical uncertainty for $V + \text{jets}$ events, which in turn affects the modelling of the event distributions and can contribute a large source of uncertainty to analyses where these events form the dominant backgrounds. The calculations are implemented in various Monte Carlo (MC) generators, the most accurate of which is MCFM [21], providing NLO predictions for up to two jets in the final state at parton level. However, not including the underlying event and

hadronisation processes restricts the use of this generator in terms of comparisons with actual data, so various other generators which include the parton showering are used in actuality:

- Pythia [22, 23] is a commonly used event generator in high energy physics, designed for general purpose with relatively large predictive power despite easy event handling. The latest version (Pythia 8 [23]) is coded in C++ and is based on dipole showering. It is able to simulate hadron-hadron, hadron-lepton, and lepton-lepton interactions with various customisations, and interfaces to Photos [24] for simulation of Bremsstrahlung radiation. However, its drawback is that the hard scattering calculations are done only to LO, and higher order corrections are approximated using the parton showering, so its performance degrades somewhat as the jet multiplicity in events is increased. Pythia uses the Lund string model for hadronisation [25], and a well-developed multiple-interaction model for the underlying event.
- HERWIG (Hadron Emission Reactions With Interfering Gluons) [26] is another general purpose generator (similar to Pythia). Its main differences are in the angular-ordered parton showers, and the process of hadronisation which uses the cluster model [27]. The latest version, Herwig++ (based on C++), includes a multiple-interaction model for the underlying event, but the original Fortran version needs to be interfaced to a separate module (JIMMY).
- JIMMY [28] is a set of library routines which are linked with HERWIG to provide multiple parton scattering events in hadron-hadron, photon-photon or photon-hadron collisions.
- ALPGEN [29] is a generator with the prime advantage that it implements the exact LO matrix calculations for multiparton final states, making it a preferred generator for analyses with jets. The hard calculation is interfaced with HERWIG for the hadronisation process, and JIMMY for the underlying event modelling.
- MC@NLO [30] is a package for combining a Monte Carlo generator with full NLO calculations of rates for hard scattering processes, making it important for use in precision measurements. The hadronisation and parton showering are again handled by HERWIG.

- Finally, POWHEG (POsitive Weight Hardest Emission Generator) [31, 32, 33] is another method for interfacing NLO QCD calculations with the parton shower generators, although POWHEG produces events with a constant weight. It can be interfaced with any modern shower generator (most commonly, Pythia and HERWIG).

Chapter 3

The LHC and ATLAS at CERN

3.1 A Brief History of CERN

The Large Hadron Collider is just the final (and most recent) step in a long succession of particle accelerators at CERN. The first accelerator built on-site was the 600 MeV Synchrocyclotron (SC), which lasted for 33 years. This provided beams for CERN's first nuclear and particle physics experiments, and then later provided beams for a radioactive ion beam facility called ISOLDE, whose experimental reach covers nuclear, astro- and medical physics.¹ Its successor was the Proton Synchrotron (PS) which was for a brief period the world's highest-energy particle accelerator at 28 GeV, paving the way for CERN's research into particle physics. This accelerator still provides beams for experiments today.

The Super Proton Synchrotron (SPS), commissioned in 1976, was the first of CERN's accelerators to cross the Franco-Swiss border. Seven kilometres in circumference, it was (and still is) fed by the PS, providing beams to two large underground experimental areas, UA1 and UA2, where, amongst their many research highlights, the W and Z bosons were discovered. The SPS consists of 1317

¹The SC shut down when ISOLDE was transferred to a different accelerator, where it remains to this day, and a good sized component of the South African participation at CERN works in the ISOLDE research programme.

conventional² electromagnets, handling various types of particles such as sulphur and oxygen nuclei, electrons, positrons, protons and antiprotons in its (ongoing) lifetime.

Subsequently the largest civil engineering project in Europe up to that time was undertaken: the excavation of a 27 km circumference tunnel 100 m below ground level, to house the Large Electron Positron accelerator (LEP). The tunnel was completed in February 1988, the two ends aligning within one centimetre of error. With over 5000 magnets and 128 accelerating cavities, LEP collided electrons and positrons provided by the SPS, allowing four large detectors, ALEPH, DELPHI, L3 and OPAL, to conduct a detailed study of the electroweak interaction, and proving that there are three (and only three) generations of fermions. After 11 years of operation LEP was shut down, and the conversion of the tunnel from an electron-positron collider to a hadron collider began.

3.1.1 The Large Hadron Collider project

Even four years before the LEP tunnel was completed discussions were in progress for the future of CERN's accelerator programme, and the LHC project was initially proposed. In the subsequent years the project's necessity fell into some doubt, as the USA approved and then started construction on the Superconducting Super Collider (SSC); however the Director General of CERN at the time, Carlo Rubbia, fought to keep the project alive. This proved to be a prudent move, as the SSC project was cancelled in 1993 owing to rising costs, and the LHC was approved a year later. During this time, the ALICE, ATLAS and CMS collaborations had published letters of intent, and their projects (as well as LHCb) were approved a few years later. Excavation began on the experimental caverns shortly thereafter, the ATLAS cavern being the first to be completed in 2003.

3.1.2 The ATLAS collaboration

The ATLAS collaboration was officially formed in 1992, when a letter of intent for “A General-Purpose pp Experiment at the LHC at CERN” was submitted to the LHC Experiments Committee [34]. Two years later, the technical proposal was submitted [35], and in 1997 the committee approved

²i.e. room temperature

the construction of the detector. Manufacture of the detector components began at individual institutions around the world, and were shipped to CERN to be assembled in the newly-excavated cavern from 2003. Initially supported by 88 institutions, the collaboration grew steadily over subsequent years, and today consists of around 3000 scientists spanning 38 countries and 177 institutions worldwide. The South African cluster officially joined the ATLAS collaboration in July 2010, after two years of association with Brookhaven National Laboratory (BNL).

3.2 The LHC at Present

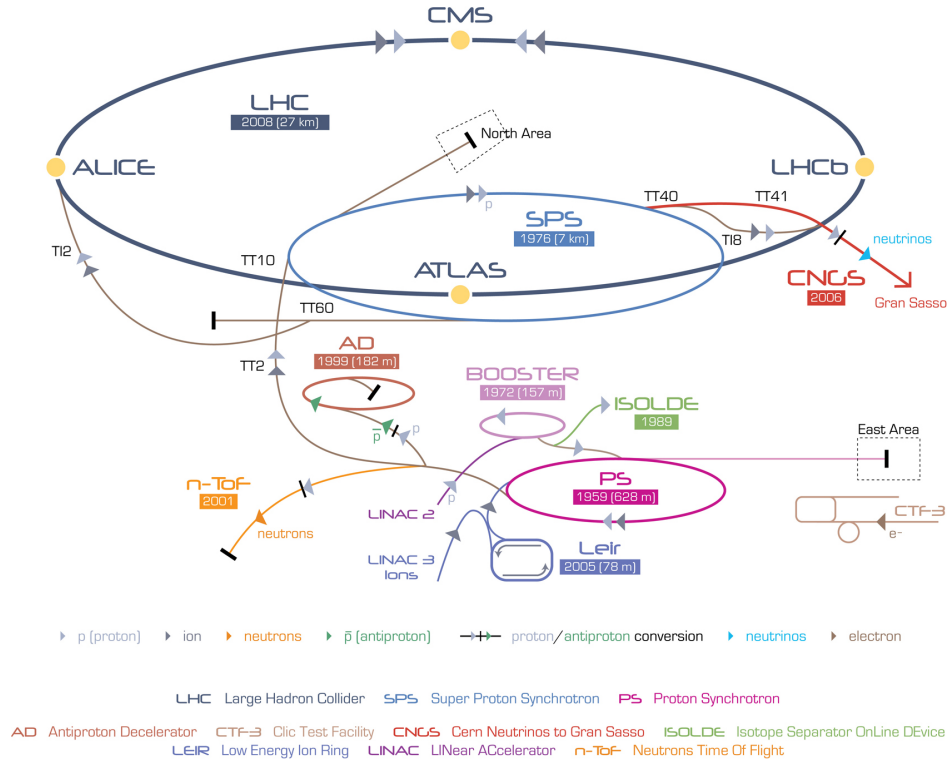


Figure 3.1: Diagram of the CERN Accelerator Complex (not to scale). © CERN.

Today, the wonderfully messy process of converting quarks and gluons into signatures of heavy particles begins with a simple bottle of hydrogen gas. Protons are stripped of their electrons with the use of an electric field, and then sent down LINAC 2, obtaining an energy of 50 MeV in the process (see the diagram in figure 3.1 for an overview).³ The beam is sent through the Proton

³The CERN accelerator complex includes many other facilities in addition to the LHC, such as the Antiproton Decelerator, ISOLDE, the Compact Linear Collider (CLiC) test area, and the North and East experimental areas. It also feeds neutrinos to Gran Sasso in Italy (CNGS) and neutrons to the Neutron Time of Flight (nTOF) facility. Furthermore, protons are not the only particles used in the LHC: lead ions from a source of vaporised lead are sent

Synchrotron Booster (PSB), accelerating to 1.4 GeV, and then on to the PS, where the protons are not only accelerated to 25 GeV, but also pulsed into bunches with the spacing and frequency as used by the LHC. These bunches are then sent through transfer lines TT2 and TT10, feeding into the SPS which further accelerates the proton bunches to 450 GeV.

Finally, the protons are injected into their counter-rotating orbits in the two ultra-high vacuum beampipes of the LHC via the transfer lines TI2 and TI8, completing a “fill” of the beamline in around 4.5 minutes. After the fill has completed, a further 20 minutes are required to accelerate the proton bunches to their maximum energy of 4 TeV (in 2012) through the use of 8 superconducting radiofrequency (RF) cavities⁴ per beam. The RF cavities generate an oscillating electric field with a frequency of 400 MHz, and protons passing through the cavities experience a force in the direction of the field. The RF cavities not only accelerate the protons but also aid in keeping the bunches well defined; protons towards the edges of a bunch arriving either earlier or later than the synchronous protons in the centre will be delayed or accelerated respectively.

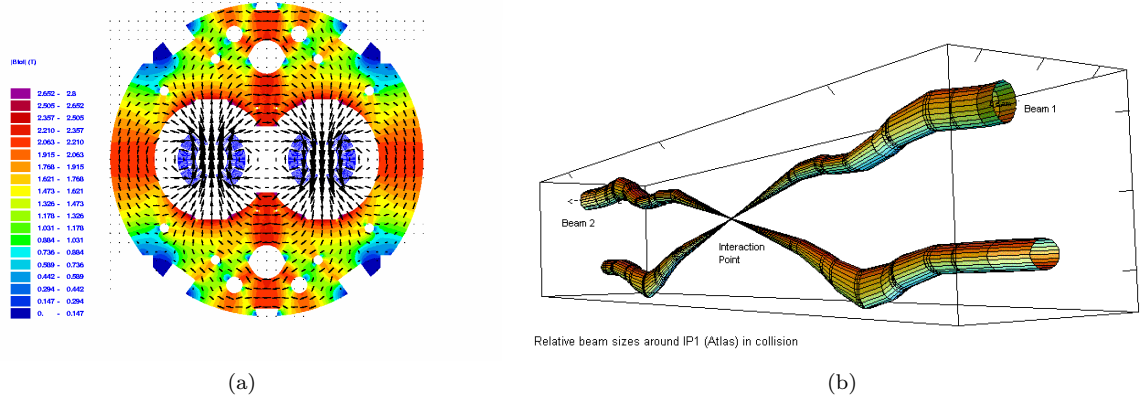


Figure 3.2: Schematic of the magnetic field inside one of the LHC dipole magnets (a), and a simulation of the relative beam sizes around the ATLAS interaction point (b). © CERN

In synchronisation with the increase in the beam energy from the RF cavities, the magnetic field applied to the proton beam must increase in order to keep the radius of curvature of the beam constant and within the arc of the beampipe. This is achieved through the use of 1232 superconducting dipole magnets, each with a length of 14.3 m and a peak magnetic field strength of 8.3 T, and each bathed in superfluid helium at a temperature of 1.9 K. The dipole field is complex (shown in figure 3.2 (a)), pointing in opposite directions across the two beampipes and hence allowing the

down LINAC 3 to the Low Energy Ion Ring (LEIR). After being sent to the PS they follow the same route as the protons on to the LHC and collisions.

⁴Two groups of four.

two counter-rotating proton beams to be controlled simultaneously within the same magnet. A further 858 quadrupole magnets and 6200 correction magnets are used for focusing and correcting aberrations within the accelerator.

Once the maximum energy is achieved and stable beams are declared, the beams are then set for physics data-taking, squeezing the bunch size down from around 1 mm to 16 μm in order to increase the beam luminosity and hence the probability of collision at the interaction points (figure 3.2 (b)). The record time for a single fill in stable beams in 2012 was 22.8 hours, though the average beam lifetime is nominally around 10 hours, with losses occurring from the pp collisions, collimators, inelastic p -gas scattering, emittance growth, and various other factors.

3.2.1 Luminosity

Since the (re)start of operations in March 2010, the LHC has three years of greatly improved performance. By far the 2012 year outshone the rest, with 4 TeV energy per beam allowing a centre-of-mass collision energy of 8 TeV, and the highest peak instantaneous luminosities yet recorded. Running from March to December, with improved beam stability allowing an average integrated luminosity rate of about 1 fb^{-1} per operational week, the 2012 run delivered a total of 23.3 fb^{-1} each to the ATLAS and CMS experiments, with an uncertainty on the integrated luminosity of $\pm 2.8\%$. The uncertainty was derived, following the same methodology as that detailed in Ref. [36], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012. A summary of the total integrated luminosity collected by ATLAS is shown in figure 3.3.

The luminosity of a proton-proton collider is a measure of the number of pp collisions that can be produced per cm^2 per second, and can be calculated as

$$\mathcal{L} = \frac{\mu n_b f_r}{\sigma_{inel}} \quad (3.1)$$

where μ is the average number of inelastic interactions per bunch crossing, σ_{inel} is the inelastic pp cross section, and there are n_b proton bunches circulating with frequency f_r in the accelerator.

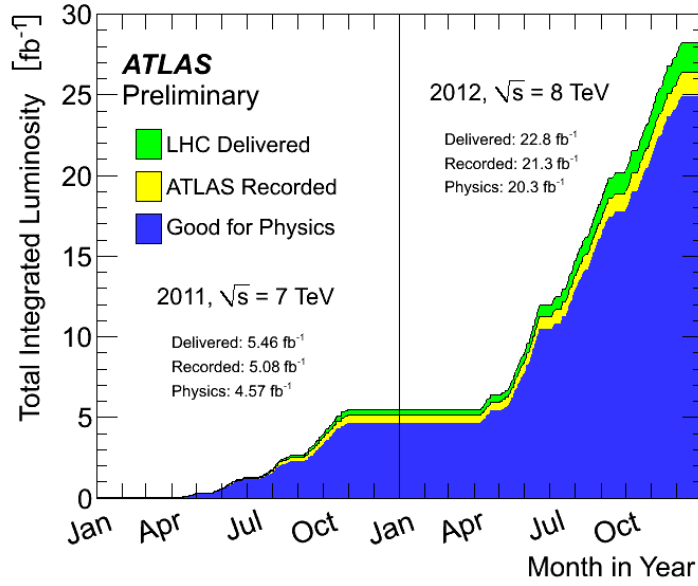


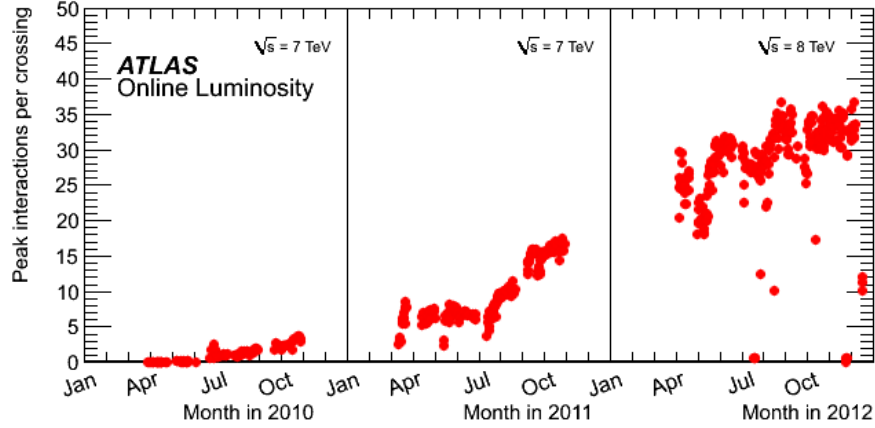
Figure 3.3: Cumulative luminosity versus time delivered to (green), recorded by ATLAS (yellow), and certified to be good quality data (blue) during stable beams for pp collisions at 7 and 8 TeV centre-of-mass energy in 2011 and 2012. The delivered luminosity accounts for the luminosity delivered from the start of stable beams until the LHC requests ATLAS to put the detector in a safe standby mode to allow a beam dump or beam studies. The recorded luminosity reflects the DAQ inefficiency as well as times when, for various reasons, the LHC was delivering collisions but ATLAS was not recording. Finally, the “Good” assessment reflects the data recorded that is suitable for physics analysis. [37, 38]

Alternatively, the luminosity can also be obtained semiquantitatively from the square of the number of protons N_p^2 in the bunches (since each proton in the first bunch might collide with any other proton from the second bunch) times the frequency f_r , and divided by the area of the bunch at the interaction point (given by $4\pi\sigma^2$, where $\sigma = 16 \mu\text{m}$):

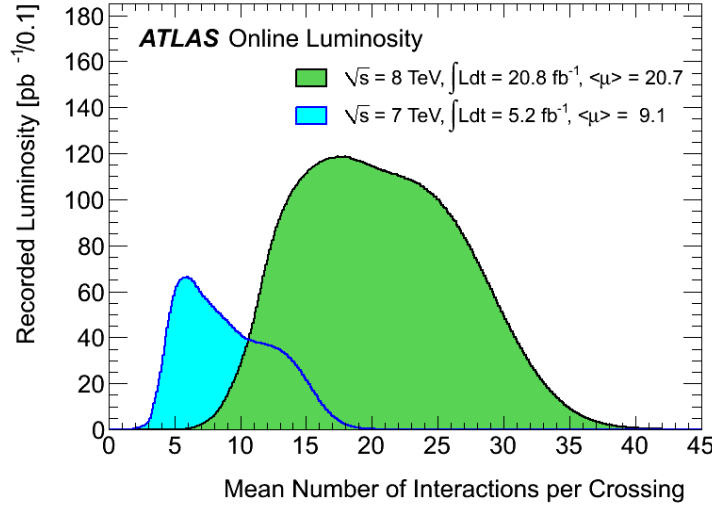
$$\mathcal{L} = \frac{f_r N_p^2}{4\pi\sigma^2} \quad (3.2)$$

High integrated luminosity is important for most new physics searches nowadays as the event configurations probed are often extremely rare compared to known processes, or suffer from large backgrounds. A high instantaneous luminosity is therefore required, which amounts to having the largest number of proton-proton collisions in the smallest possible area at each interaction point. In 2012, the LHC ran with 1380 bunches of protons with a maximum bunch intensity of 1.7×10^{11} protons per bunch, spaced at 50 ns intervals. Combined with the tight squeezing of the beam before the interaction points, this bunch spacing resulted in a peak instantaneous luminosity for the 2012 run

of $7.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, which translates to, on average, 21 individual proton-proton collision events every 50 ns (every bunch crossing). Figure 3.4 shows the peak number of interactions measured by ATLAS as a function of time over the first LHC run, as well as a comparison between the average number of interactions in 2011 and 2012.



(a)



(b)

Figure 3.4: Peak number of interactions per LHC bunch crossing in 2010, 2011 and 2012 (a); and a comparison of the mean number of interactions per bunch crossing between 2011 and 2012 (b). [36]

Of course, most of these collisions do not produce a hard scatter event: we may expect one hard process, while the rest are the dominant soft interactions (described in chapter 2) such as diffraction, multiple-parton interactions, and soft initial- and final-state radiation. These additional interactions are referred to as in-time pileup, and they contribute particles in the detector which detract from the measurement of the primary interaction. For an idea of what this looks like within the detector,

figure 3.5 shows an event recorded by ATLAS with 25 individual resolved vertices, one of which is a candidate for a Z to dimuon decay.

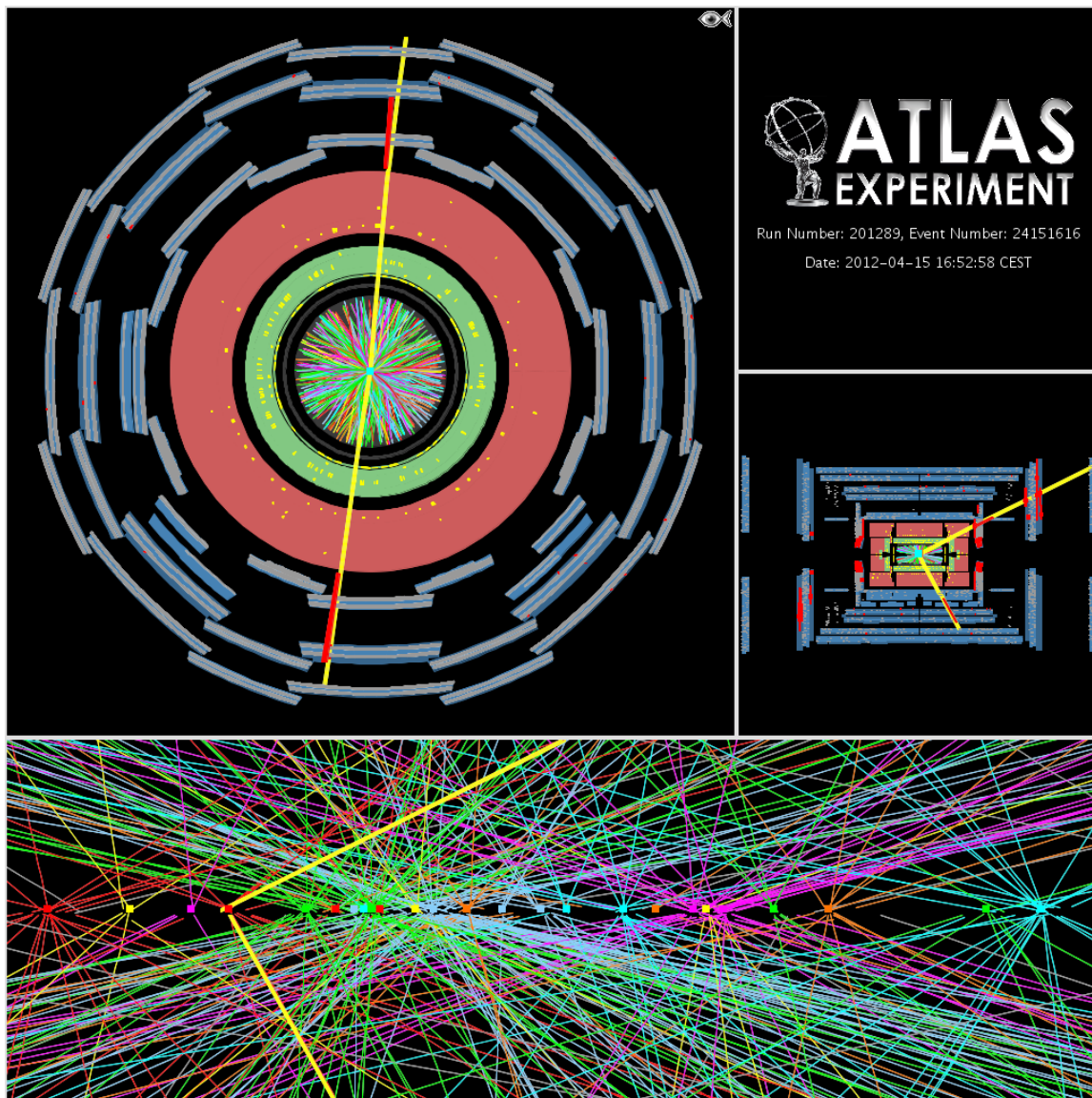


Figure 3.5: A candidate Z boson decaying to a muon pair, with 25 reconstructed vertices in the event, recorded on April 15th 2012. © ATLAS

3.3 The ATLAS Detector

The ATLAS detector (figure 3.6), located at Point 1 around the LHC ring, is a multipurpose system of particle detectors with a forward-backward symmetric cylindrical geometry and near 4π solid angle

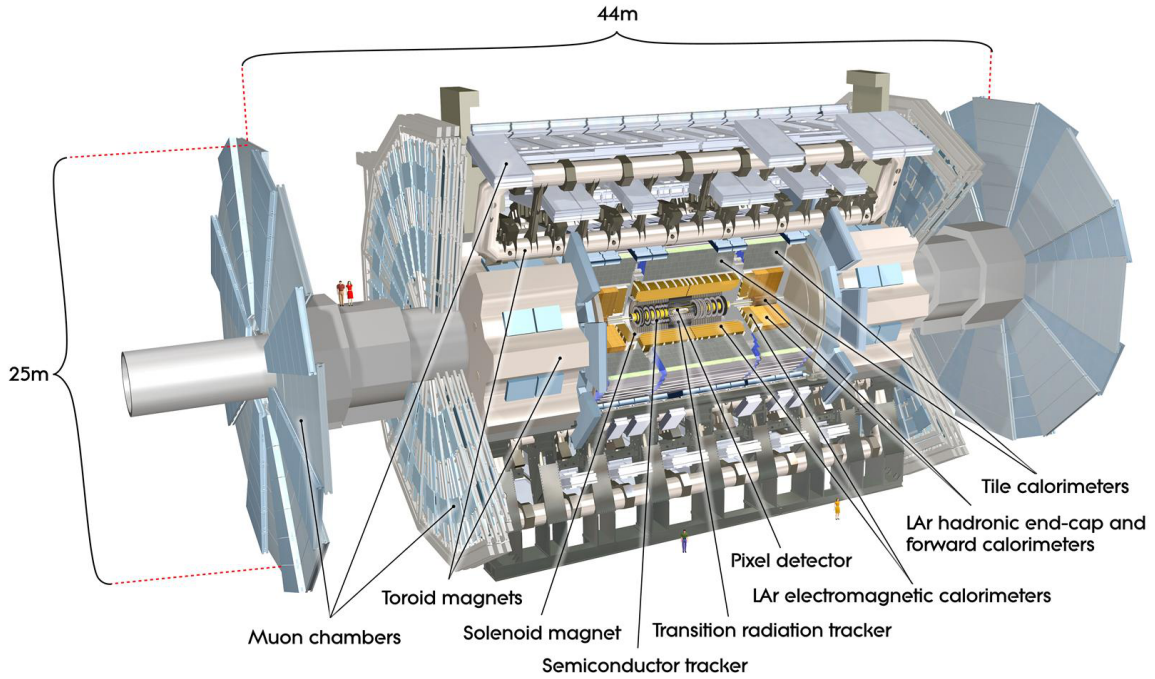


Figure 3.6: Computer-generated model of the ATLAS detector and its subsystems. © ATLAS

coverage. It is composed of 4 core systems arranged in a barrel-plus-endcaps format⁵: the Inner Detector (ID), which provides precision tracking and momentum resolution in the region closest to the beam pipe; the Electromagnetic and Hadronic Calorimeters, which measure the transverse energy originating from the collisions and are used for electron, photon and hadron identification; the Muon Spectrometer (MS) for additional accurate muon momentum measurements and identification; and the solenoid and toroid magnet systems for charge and momentum determination. A brief description of these systems follows, with focus on the tracking and vertexing which is important for the focus of this study, as well as some detail about the calorimeters and missing energy measurement that is useful for context.

A note on the coordinate system used: in ATLAS (as with most collider physics experiments), the positive x -axis is defined as pointing from the interaction point to the centre of the LHC ring, the positive y -axis is defined as pointing upwards, and the positive z -axis corresponds to protons running anticlockwise. The polar angle θ is measured from the beam axis (z -axis), the azimuthal angle ϕ is measured in the transverse (xy)-plane, and the pseudorapidity is defined by $\eta = -\log(\tan(\theta/2))$.

⁵The barrel-region detectors are arranged in concentric cylinders parallel to the beam axis, while the endcap detectors are disks oriented perpendicular to the beam axis.

3.3.1 The Inner Detector (ID)

The ID covers the pseudorapidity range $|\eta| < 2.5$ [39, 40] and is designed for precise track reconstruction. Immersed in a 2 T solenoidal magnetic field, it is comprised of three subdetectors, a silicon pixel detector, a silicon microstrip semiconductor tracker (SCT) and a straw-tube transition radiation tracker (TRT, within the $|\eta| < 2$ range only).

Every bunch crossing, there are of order 10^3 particles emerging from the collision point within the acceptance of the tracking detectors. Despite this large track density, high precision momentum resolution is required to achieve the sensitivity necessary for the intended physics processes to be studied. In addition, excellent track reconstruction and primary vertex identification is essential in the context of the track-based missing transverse momentum, given the large number of pileup interactions in 2012.

The discrete, high resolution silicon detectors are designed to provide the finest resolution, with the highest granularity around the vertex region from the pixel detectors. The pixel sensors are identical, segmented in R - ϕ and z with dimensions $50 \times 400 \mu\text{m}^2$, providing an intrinsic accuracy in the barrel region of $10 \mu\text{m}$ in the R - ϕ plane and $115 \mu\text{m}$ in z (R, endcaps). Typically, each track from the interaction point will cross three pixel layers. The innermost layer (also called the B-layer) is located just outside the beam pipe at a radius of 50 mm, and aids in precision reconstruction of both primary and (in conjunction with the SCT) secondary vertices. The detector has approximately 80.4 million channels for readout.

Layers of the SCT strips surround the pixel detector, with intrinsic accuracies per module of $17 \mu\text{m}$ in the R - ϕ plane and $580 \mu\text{m}$ in z (R, endcaps). Each track crosses eight of these strips (corresponding to four spatial points), with the readout channels numbering 6.3 million. Along with the pixel B-layer, the semiconductor trackers also allow impact parameter measurements and vertexing for heavy flavour and τ lepton tagging.

While the two inner silicon-based detectors provide excellent tracking precision, the surrounding TRT is able to generate and detect transition radiation from traversing particles, allowing differentiation between electrons and charged hadrons. The 4mm diameter straw tubes, filled with a xenon-based

gas mixture, produce a large number of hits per track (typically around 36) with an accuracy of $130\ \mu\text{m}$ in the $R\text{-}\phi$ plane. The TRT does not provide information in the z direction.

Together, the combination of the precision trackers at small radii close to the beam pipe with the TRT at a larger radius gives very robust pattern recognition used in the track reconstruction algorithms, and despite the lower precision per point of the TRT, it contributes significantly to the momentum measurement owing to the longer measured track length.

Track and Vertex Reconstruction

The ATLAS ID track reconstruction software reconstructs charged particle tracks with transverse momentum $\mathbf{p}_T > 0.4\ \text{GeV}$ and $|\eta| < 2.5$ in a three-stage formalism [41]. First, the raw data from the pixel and SCT are converted into clusters and space-points, and the TRT raw timing information is converted into drift circles.

During the second “track-finding” stage, track seeds are formed from a combination of space points in the pixel layers and first SCT layer, and then extended throughout the SCT to form track candidates. These candidates are then fit, with various quality checks performed to increase reconstruction performance and reduce the number of fake tracks. The selected tracks are extended into the TRT where possible using the drift circle information, helping to resolve directional ambiguities. The tracks are then refit with the full information, and the highest quality result between the two- or three-detector fit is retained. The ID momentum resolution depends heavily on the $\mathbf{p}_T$ of the track as well as its pseudorapidity, ranging from about 1.9% for 25 GeV central tracks to 11% for 100 GeV tracks towards the edge of the detector. As the track $\mathbf{p}_T$ increases, the resolution deteriorates even more, up to almost 50% for tracks near 400 GeV at high η [42].

Finally, in the post-processing stage, a dedicated vertex finder [43] reconstructs vertices from the collection of tracks, with some extra quality requirements on the tracks used for the vertex fit. However, tracks not associated with any vertex are also kept for use in analyses, and all information about the tracks and vertices are stored in the Event Data Model. The vertex reconstruction

efficiency decreases as the number of interactions increases, from 90% for a single interaction with charged particle tracks to about 50% at $\mu = 41$ [44].

The reconstructed vertices are ordered, and the vertex with the highest $\sum(p_T^{track})^2$ is considered the primary vertex (PV) where the hard interaction occurred. All vertex-related track quantities, such as their impact parameters, can in principle be calculated with respect to any of the reconstructed vertices, though most often we just refer to these with respect to the hard PV.

3.3.2 The Electromagnetic and Hadronic calorimeters

While the ID provides precision tracking of charged particles, the calorimeters are equally important, accurately measuring the energies and positions of electrons, photons and hadrons - both charged and neutral - as well as of the missing transverse energy of an event. Calorimeters also provide crucial information for particle identifications, allowing one to distinguish electrons and photons from jets (or other hadrons) and aiding in the identification of hadronically decaying tau leptons.

The layout of the ATLAS calorimeters is described in detail in [45, 46]. The major components are the liquid argon (LAr) electromagnetic barrel and endcap (EMB and EMC) calorimeters, the tile scintillator hadronic barrel (TileCal), the LAr hadronic endcap (HEC), and the LAr forward calorimeter (FCAL).

The high granularity EMB and EMC calorimeters use lead absorbers with a LAr ionization medium, and cover the pseudorapidity range $|\eta| < 3.2$ with an accordion-style geometry that allows full coverage in ϕ . Longitudinally they are separated into three layers (strips, middle, and back) with the middle layer accounting for around 80% of the energy of each electromagnetic shower. In addition, a presampler (PS) covers the region $|\eta| < 1.8$ to aid in the measurement of the energy of particles that start showering before the calorimeter. The TileCal surrounds the LAr cryostats and is composed of three layers of iron absorbers with plastic scintillator tiles within $|\eta| < 1.7$, while the four-layered HECs use copper plate absorbers with LAr owing to the high radiation doses in the forward regions ($1.5 < |\eta| < 3.2$). Finally, the FCAL covers the region $3.1 < |\eta| < 4.9$, with one

layer made of copper and optimised for electromagnetic interactions, and two tungsten layers for the hadronic particles. Again LAr is used due to the amount of radiation in this region.

The intrinsic energy resolution of a calorimeter has two components: a sampling term which is a function of the incoming particle energy and scales as $\frac{1}{\sqrt{E}}$, and a constant term which covers the geometry and material of the calorimeter. The design resolutions for the ATLAS LAr and Hadronic calorimeters are given by

$$\frac{\sigma_E^{\text{LAr}}}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\% \quad (3.3)$$

$$\frac{\sigma_E^{\text{Had}}}{E} = \frac{52.9\%}{\sqrt{E}} \oplus 5.7\% \quad (3.4)$$

which, for the sake of illustration, gives a resolution of 5% to 1.6% for EM particles of between 10 and 50 GeV.

Two main sources of noise affect the calorimeter resolution. The first is from the readout electronics, and can be reduced to some degree with thresholds, offline calibrations, and the online masking of hot cells during data-taking. The other source comes from pileup, such as the in-time pileup already mentioned, with the energies of particles from extra interactions in the same bunch crossing overlaid with those from the primary interaction. A second source of pileup also affects the calorimeter: dubbed out-of-time pileup, this originates from interactions from different bunch crossings that are close in time to the current primary interaction, as the response time of the calorimeter (up to 600 ns depending on η) is very large relative to the 50 ns bunch spacing.

3.3.3 The Muon Spectrometer (MS)

Finally, the muon spectrometer [47] surrounds the calorimeters, consisting of three large air-core superconducting toroid magnets, precision tracking chambers providing accurate muon momentum measurement out to $|\eta| < 2.7$, as well as additional detectors for muon triggers in the region $|\eta| < 2.4$.

The muon reconstruction algorithms either use the MS information on its own or in combination with ID (and calorimeter) information to provide the best measurement of the muon momentum, for muons between 3 GeV and 3 TeV. The ID provides the best measurement of track momenta at low to intermediate momenta, while the MS performance dominates for momenta above about 30 GeV, since the toroidal magnetic field provides excellent momentum resolution even for high energies (10% for 1 TeV muons).

3.4 Data and Monte Carlo Samples for the 2012 LHC Run

The data used for the work described in this thesis result from ATLAS recorded data in 2012, with stable proton beams from the LHC at a $\sqrt{s} = 8$ TeV centre of mass energy colliding under nominal ATLAS magnetic field conditions. Individual detector subsystems flag good quality data where the calorimeters, ID and MS are fully operating, and remove those events where the event data was only partially recorded. Further selection criteria are also applied, reducing the impact of instrumental noise and out-of-time calorimeter deposits from cosmic ray and beam backgrounds. The final dataset from 2012 after cleaning and passing the “Good” assessment [38] suitable for physics analysis therefore corresponds to a total integrated luminosity of about 20.3 fb^{-1} .

Monte Carlo samples of $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu + n \text{ jets}$ ($\ell = e, \mu, \tau$) production were generated using ALPGEN [29] interfaced to Jimmy [28], with up to 6 partons in the final state. Inclusive pp to V samples using the POWHEG [31, 32, 33] model were also used for comparison, where the final state partons were produced by Pythia [22, 23] using the CT10 NLO PDF [17] and the ATLAS AU2 tune [48]. The $t\bar{t}$ events were produced with the MC@NLO event generator [30], and the WW, WZ, and ZZ diboson samples were produced using HERWIG [26].

Multijet background events prove to be more of a difficulty, though the events are still generally well modelled at the generator level. However, the detector response to these events is not described well, with discrepancies in the fake rates and identification efficiencies, so many analyses rely on a data-driven background estimation. In this work, we do not include the multijet processes in our background estimation, and make note where these have an effect on our distributions.

Of course, the primary processes of interest are not the only interactions involved in the LHC collisions, and the simulations of these need to be folded in with those of the additional pileup interactions occurring within the same bunch crossing. These interactions, known as minimum bias events, are generated using Pythia with the MSTW08 leading order PDF [10] and the ATLAS MC12 A2M tune [48], and contain contributions from single- and double-diffractive processes as well as inelastic pp scattering, according to their relative cross sections.⁶ The simulated MC minimum bias samples are weighted during the analysis to obtain a similar distribution of the average number of interactions per bunch crossing to that observed in the data.

As a final step in the modelling, the generated particles are propagated through a GEANT4 [49] simulation of the ATLAS detector, taking particle-matter interactions into account [50]. The simulated events are then reconstructed using the same algorithms as are used on the data, following similar trigger requirements and performances as the real events.

⁶Contributions from elastic scattering of the protons are not seen by the detectors as they typically result in the particles escaping down the beam axis.

Chapter 4

Track-Based Missing Transverse Momentum in ATLAS

The standard $\mathbf{E}_T^{\text{miss}}$ algorithm in ATLAS during Run 1 used energy deposits in the calorimeters and muons reconstructed in the muon spectrometer to reconstruct the $\mathbf{E}_T^{\text{miss}}$ for each collision event. The calorimeters extend to large pseudorapidities to reduce the number of high energy particles in the collision that are lost in the forward directions, and the fine granularity allows for good energy resolution of the clusters used for object and $\mathbf{E}_T^{\text{miss}}$ reconstruction. However, the transition regions between the various parts of the calorimeters contain inactive material, and there may be dead regions and various sources of noise as well as cosmic rays and beam-halo muons that cross the detector. All these effects can contribute to fake energy or mismeasurement of particle energies, and therefore fake signals of $\mathbf{E}_T^{\text{miss}}$ in the calorimeters, though selection criteria for the clusters are applied to minimise their impact.

The large number of pileup interactions in each LHC bunch crossing also contribute energy to the calorimeter clusters on a non-uniform, per-event basis, inexorably interwoven with that originating from the hard scattering event. Several methods have been developed to suppress such contributions from a reconstruction standpoint, but pileup still remains a serious challenge and one that will only

increase with LHC luminosity. In fact, it is on the point of pileup where the main advantage of this work rests.

4.1 Motivation

Ideally the $\mathbf{E}_T^{\text{miss}}$ ought to be calculated using the final state particles from the hard scatter vertex only, summing the momentum contributions from both charged and neutral particles over the full phase space. In reality, of course, the practicalities of particle accelerators and detectors disallow this for the reasons mentioned above, and we are left with a method that considers charged and neutral particles from *all* scattering vertices in the event (within the η, ϕ acceptance). However, the precision of the ATLAS Inner Detector allows the reconstruction software to trace the paths of charged particles back to their point of origin, where individual scattering vertices can be resolved, and the tracking and vertexing algorithms then associate each track in the event to a particular collision vertex. We are hence able to calculate the missing transverse momentum and scalar Σp_T based only on charged-particle tracks originating from the hard interaction¹ (or, in fact, any of the individual interaction vertices).

This pileup-independent measurement of the track-based missing transverse momentum, $\mathbf{p}_T^{\text{miss}}$, complements the $\mathbf{E}_T^{\text{miss}}$ measurement, and can be used either on its own or in conjunction with the calorimeter-based quantity in analyses where real $\mathbf{E}_T^{\text{miss}}$ plays an important role. It can also provide a more accurate measurement of the hard interaction's $\mathbf{E}_T^{\text{miss}}$, especially in events with low real $\mathbf{E}_T^{\text{miss}}$ where contributions from pileup and external factors may outweigh the contribution originating from the primary vertex. Additionally, the $\mathbf{p}_T^{\text{miss}}$ has a better sensitivity to reject cosmic ray and beam halo backgrounds, since most of their tracks have different time and geometry signatures compared to tracks from the collisions.

¹Recall the hard - or primary - vertex is defined as the vertex with the highest scalar $\sum(p_T^{\text{track}})^2$.

4.2 Limitations

Of course, the track-based approach also has its limitations, most notably the omission of neutral particles originating from the hard interaction: since neutral particles do not leave tracks in the inner detector their momenta cannot be measured or included in the calculation. Large contributions to the total transverse momentum from neutral particles therefore show up as sources of fake $\mathbf{p}_T^{\text{miss}}$, broadening the $\mathbf{p}_T^{\text{miss}}$ distribution and degrading its resolution. This is particularly noticeable in events with high $\mathbf{p}_T$ jets, as jets are composed of about 60% charged particles [51], so we miss about 40% of the jet's momentum in our calculation.

The ATLAS tracking detectors also have a smaller geometrical coverage than the calorimeters, extending out to only $|\eta| < 2.5$, so contributions from both charged and neutral particles in the forward regions are lost. In addition, the track momentum resolution also degrades as the $\mathbf{p}_T$ of the tracks increase, as higher $\mathbf{p}_T$ tracks bend less in the solenoidal magnetic field, reducing the quality of the track fit. And finally, tracking efficiency also decreases in dense environments, such as the core of a highly boosted jet, which could also degrade the performance of the $\mathbf{p}_T^{\text{miss}}$. For each of these limitations we have adapted the $\mathbf{p}_T^{\text{miss}}$ algorithm in various ways to compensate for their effects, which will be described in detail in section 4.4.

4.3 Physics Object Selection

4.3.1 Primary vertex and general track selection

Good primary vertex identification and track reconstruction are crucial given the large number of pile-up interactions in the data (recall figure 3.5). We use the definition of the main primary vertex (PV) as calculated by the vertex finding algorithm described in section 3.3.1, defining the PV as that with the largest value of $\sum(p_T^{\text{track}})^2$. This definition is more than 90% efficient for W and Z events [44, 52] though separate considerations need to be made for events where the final state particles do not show up in the ID (such as the Higgs boson decay to two photons).

To ensure a good measurement of the missing transverse momentum, the tracks included in the $\mathbf{p}_T^{\text{miss}}$ calculation need to satisfy a number of quality requirements:

- $p_T > 500$ MeV
- $|\eta| < 2.5$
- At least 1 pixel detector hit
- At least 6 SCT hits
- Transverse impact parameter with respect to the primary vertex $|d_0| < 1.5$ mm
- Longitudinal impact parameters with respect to the primary vertex $|z_0 \times \sin(\theta)| < 1.5$ mm.

The 500 MeV lower bound on the reconstructed momentum of the selected tracks ensures that they extend through to the outer layers of the ID, while the η cut keeps the track within the full acceptance of the ID. The requirements on the number of hits in the pixel and SCT subdetectors help to ensure a good calculation of the track momentum from the reconstruction algorithms. Also, the reconstruction of very low $\mathbf{p}_T$ tracks is extremely difficult owing to their large curvature and high degree of multiple scattering within the detector, and increases the reconstruction time and size of the output datasets unwarrantedly. The $\mathbf{p}_T$ cut can also reduce the contribution from pileup tracks, as particles produced from minimum bias events typically peak at lower values of the $\mathbf{p}_T$, though this is achieved with a far higher efficiency through the impact parameter cuts. Here, d_0 and z_0 denote the impact parameters of the tracks in the transverse and longitudinal directions respectively. Since the beam spot at the time of interaction extends much further in the longitudinal direction than the transverse, the cut on z_0 has the greatest effect of reducing the contributions of tracks from pileup vertices, while the d_0 cut reduces those originating from secondary vertices.²

The selections above remove the majority of tracks we wish to exclude from the $\mathbf{p}_T^{\text{miss}}$ calculation (those originating from pileup vertices and tracks that are most likely to have bad momentum

²Secondary vertices are defined as those produced from the decay of an unstable particle, or from a subsequent interaction of a particle (such as bremsstrahlung).

reconstruction), and provide a good initial approach to calculating the $\mathbf{p}_T^{\text{miss}}$ [53]. However, tracks passing the above criteria may still have misreconstructed momenta, which can affect the overall $\mathbf{p}_T^{\text{miss}}$ by distorting its direction or producing a large tail in the distribution. These tracks can be classified into three groups, and additional requirements optimised for each type of track have since been imposed in order to reduce their impact:

4.3.1.1 Tracks surrounding high $\mathbf{p}_T$ reconstructed electrons

In some cases, reconstructed electron tracks are not isolated, but surrounded by several soft tracks from underlying event particles and photon conversions. Occasionally, however, these soft tracks may have either an extremely close or very high $\mathbf{p}_T$ compared with the main electron, indicating either a duplication or bad reconstruction of the track's momentum. In these cases we apply the following isolation requirements to reduce the bad tracks while still keeping the good electron tracks for the calculation:

- All tracks associated with reconstructed soft electrons within a distance $\Delta R < 0.05$ from a main (high $\mathbf{p}_T$) electron are rejected.
- In a cone of $\Delta R < 0.1$ around the main electrons, any track with $\mathbf{p}_T > 10$ GeV and contributing more than 25% of its momentum to the electron calorimeter energy ($E_T^{\text{electron}}/p_T^{\text{track}} < 4$) is rejected.

4.3.1.2 Tracks in dense, high $\mathbf{p}_T$ jets

Events with high $\mathbf{p}_T$ jets may have a very high pixel hit density in the inner detector, leading to an increase in combinatorial hits and possibly producing very large momentum tracks from the fitting algorithms. To reduce this effect, all tracks associated³ with reconstructed jets are checked against the jet $\mathbf{p}_T$, and are rejected if $p_T^{\text{track}} > 2 \times p_T^{\text{jet}}$.

³The association of tracks with jets is done using ATLAS's ghost association method, described in detail in [54].

4.3.1.3 Tracks with very large momentum

High momentum tracks originating from hard interactions do of course exist, and provide a large and important contribution to the $\mathbf{p}_T^{\text{miss}}$ calculation if valid. However, a low $\mathbf{p}_T$ track that interacts with the material in the ID may produce a large number of secondary particles, leaving enough hits in the pixel and SCT subdetectors to be misreconstructed as a track with a much higher momentum than the original. A study on simulated data showed that overall, such tracks total only about 0.1% of all reconstructed tracks, though they are predominantly found in the fiducial regions $|\eta| < 1.5$ for $p_T > 200$ GeV, and $|\eta| > 1.5$ for $p_T > 120$ GeV. To counter their effect, the following additional criteria are required on isolated tracks in the $\mathbf{p}_T$ and η regions described above (muon tracks are excluded from these requirements owing to their low energy signature in the calorimeter):

- The relative uncertainty on the charge to momentum ratio of the track (q/p) must satisfy $\frac{\sigma(q/p)}{(q/p)} < 0.4$
- The summed energy in the calorimeter clusters within a cone of radius 0.1 in the (η, ϕ) plane around the track should satisfy $E_T^{0.1}/p_T^{\text{track}} > 0.65$ in order to reflect the reconstructed track momentum.

For non-isolated tracks, the corresponding calorimeter energy deposit includes contributions from the surrounding tracks as well as the track of interest. In this case a cone of radius 0.2 is used to calculate the total summed momentum and energy of all tracks and calorimeter clusters respectively within the cone. Only tracks passing the following selection are used in the $\mathbf{p}_T^{\text{miss}}$ calculation:

- $p_T^{\text{track}}/p_T^{0.2} > 0.6$ and $E_T^{0.2}/p_T^{0.2} < 0.6$

Such misreconstructed tracks contribute in a large part to the tail of the $\mathbf{p}_T^{\text{miss}}$ distribution, so their exclusion is an important step in maintaining the quality of the $\mathbf{p}_T^{\text{miss}}$. Figure 4.1 shows the distribution of the track $\mathbf{p}_T$ before and after the removal of the misreconstructed tracks in $Z \rightarrow ee$ events in 2012 data. A rejection efficiency of up to 90% is achieved for these events and only a very small number of tracks with $\mathbf{p}_T > 500$ GeV are accepted.

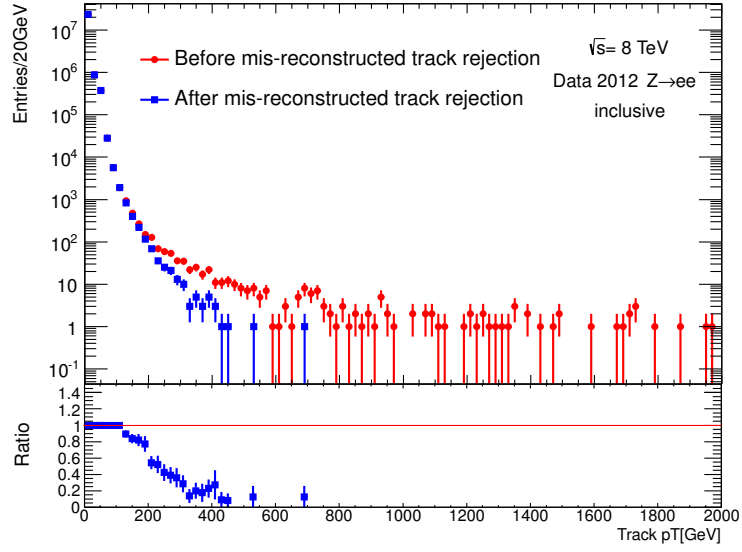


Figure 4.1: Track $\mathbf{p}_T$ distribution in $Z \rightarrow ee$ events from 2012 data before and after the misreconstructed track momentum rejection is applied. [B. Liu]

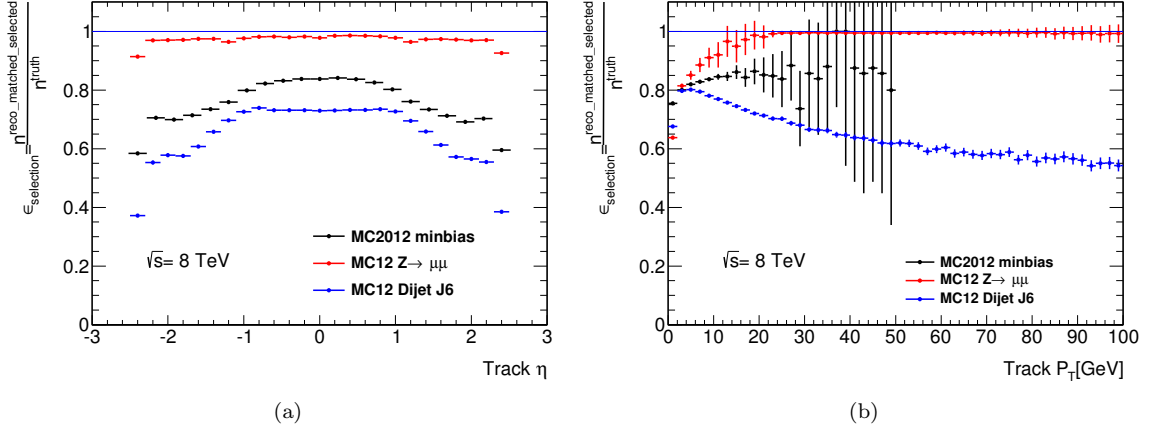


Figure 4.2: Track selection efficiency as a function of track $\mathbf{p}_T$ and η for minimum bias, $Z \rightarrow \mu\mu$ and QCD dijet (with $1500 < \mathbf{p}_T^{\text{jets}} < 2000$ GeV) events. [B. Liu]

The track selection efficiency is obtained using Monte Carlo simulation samples, matching stable truth particles of $\mathbf{p}_T > 500$ MeV and $|\eta| < 2.5$ coming from the signal vertex to tracks reconstructed by the ATLAS software. The reconstructed $\mathbf{p}_T$ and η distributions of the tracks are obtained just after the matching, and again after the tracks have passed the $\mathbf{p}_T^{\text{miss}}$ selections. The efficiency is then obtained as a function of track $\mathbf{p}_T$ and η by dividing the selected matched track distributions by the total matched tracks distributions, shown in figure 4.2 for minimum bias, $Z \rightarrow \mu\mu$ and QCD dijet events for jets of $\mathbf{p}_T$ between 1500 and 2000 GeV. The low efficiencies in QCD dijet and minimum

bias events are shown for comparison: the very high track density in the core of the dijets limits the quality of the track reconstruction; in the minimum bias events the event is dominated by low $\mathbf{p}_T$ tracks which have a higher probability of failing the other selection requirements. On the other hand, the $Z \rightarrow \mu\mu$ events, with their clear signal of well-reconstructed high $\mathbf{p}_T$ leptons plus hadronic recoil shows an excellent efficiency of selection of the tracks into the $\mathbf{p}_T^{\text{miss}}$ calculation.

4.3.2 Lepton selection

The object reconstruction algorithms in ATLAS often use information from more than one sub-detector system to obtain the best possible measurement for a given type of particle (for example, electron candidates are required to have an ID track matched to a deposit in the EM calorimeter), though the track requirements may differ from those used in our selections above. This could mean that a track used in the reconstruction of a lepton fails our general track requirements, but the leptons themselves are used for event selections in physics analyses. To maintain consistency and ensure that the tracks associated with these objects are always included in the $\mathbf{p}_T^{\text{miss}}$, general lepton candidates are selected as follows:

Muons passing the general selection must be reconstructed from a track in the muon spectrometer with a matched track in the inner detector (called “combined” muons) [55], and are required to have $\mathbf{p}_T > 6$ GeV and $|\eta| < 2.5$. Electrons are required to have a minimum $\mathbf{p}_T > 10$ GeV and $|\eta| < 2.47$, though electron candidates in the electromagnetic calorimeter transition region, $1.37 < |\eta| < 1.52$, are not considered.⁴ Electrons are also required to pass the “medium” identification criteria optimised for 2012 data [56, 57].

The tracks associated with the selected leptons are obtained using the stored track-to-object information in the data. All the associated tracks are included in the $\mathbf{p}_T^{\text{miss}}$ calculation with none of the above requirements in section 4.3.1 imposed, as a detailed study showed that 3-4% of the tracks associated with reconstructed electrons and muons fail some of the high quality requirements.

⁴The exclusion of electrons in this region is mirrored in analyses’ selection criteria.

4.3.3 Jet selection

Jets in the event are more complicated, but as with the leptons, we need to ensure that all good tracks from a given jet are included to obtain the best possible measurement of the $\mathbf{p}_T$ contribution from the jet (recall that only about 60% of the total jet $\mathbf{p}_T$ comes from charged particles), while rejecting overlapping tracks from pileup interactions. Jets are reconstructed with the anti-kt algorithm [58] using a distance parameter of $R = 0.4$, with corrections for pileup at the topocluster level, and subsequent calibrations using the LCW+JES scheme [59, 60]. Jets are selected if their calibrated $\mathbf{p}_T$ is greater than 25 GeV in the central region ($|\eta| < 2.5$), or 30 GeV in the forward region ($2.5 < |\eta| < 4.4$), and they do not overlap with any of the selected electrons. In addition, a cut on the jet vertex fraction (JVF [61]) of $\text{JVF} > 0.50$ is required for jets with calibrated $p_T < 50$ GeV and $|\eta| < 2.4$, which helps to reduce the selection of pileup jets in the central region [54].⁵

The jet tracks are obtained using the ghost association algorithm [54], and are required to pass the high quality track requirements described in section 4.3.1, as the ghost association is a geometrical matching of tracks to each jet, but does not take into account vertex requirements and track $\mathbf{p}_T$.

4.4 $\mathbf{p}_T^{\text{miss}}$ Reconstruction

Two approaches were finalised for calculating the missing transverse momentum per event: one based on tracks only (nominal $\mathbf{p}_T^{\text{miss}}$), and the other using a combination of track and calorimeter information that can be user-defined (object-corrected $\mathbf{p}_T^{\text{miss}}$).

For both, individual terms are defined with the lepton, jet, and track selections as described above. The terms are defined in a particular order to take into account any possible overlap between all the considered objects, preventing duplication of the high $\mathbf{p}_T$ objects in the calculation. Electrons are selected first, and jets second, but jets that fall within a cone of $\Delta R < 0.4$ around an already-selected electron are vetoed. Muons are selected third, and while no ΔR veto is done between muons and

⁵The jet vertex fraction is the fraction of summed $\mathbf{p}_T$ of all tracks in a jet that are associated with the primary vertex, relative to the total summed $\mathbf{p}_T$ of all tracks in the jet. The value of the JVF peaks towards +1 for jets originating from the hard scatter vertex, and 0 for jets from pileup vertices. Jets with no associated tracks (i.e. forward jets that are outside the ID acceptance) have a JVF of -1.

jets, the associated muon track is checked to ensure that it has not already been included in the jet tracks term. Finally, any other tracks in the event that are not part of any of the object-related terms, and that pass all the high quality requirements described in section 4.3.1, are grouped into a track-based soft term. The $\mathbf{p}_T^{\text{miss}}$ is reconstructed by summing these terms in two different ways: a “nominal” method, and an “object-corrected” method.

4.4.1 Nominal $\mathbf{p}_T^{\text{miss}}$

In the Nominal method, the individual terms contain the ID-based momenta of the soft tracks and the tracks associated with the leptons and jets. The x and y components of the tracks in each term are summed to form a track-only calculation of the $\mathbf{p}_T^{\text{miss}}$ components in the event, while the transverse component is summed to produce the scalar Σp_T :

$$\mathbf{p}_{x,y}^{\text{miss,nominal}} = - \left(\sum_{\text{electron tracks}} \mathbf{p}_{x,y} + \sum_{\text{muon tracks}} \mathbf{p}_{x,y} + \sum_{\text{jet tracks}} \mathbf{p}_{x,y} + \sum_{\text{soft tracks}} \mathbf{p}_{x,y} \right) \quad (4.1)$$

$$\Sigma p_T^{\text{nominal}} = \sum_{\text{electron tracks}} p_T + \sum_{\text{muon tracks}} p_T + \sum_{\text{jet tracks}} p_T + \sum_{\text{soft tracks}} p_T \quad (4.2)$$

The negative sign in the calculation of $p_{x,y}^{\text{miss}}$ is because we are calculating the *missing* momentum, which is of the same magnitude but opposite in direction to the resultant momentum of the contributing particles. The missing transverse momentum, $\mathbf{p}_T^{\text{miss}}$, can of course be calculated by:

$$\mathbf{p}_T^{\text{miss,nominal}} = \sqrt{\left(\mathbf{p}_x^{\text{miss,nominal}}\right)^2 + \left(\mathbf{p}_y^{\text{miss,nominal}}\right)^2} \quad (4.3)$$

This provides a measurement of the $\mathbf{p}_T^{\text{miss}}$ that is almost completely decoupled from the calorimeter-based $\mathbf{E}_T^{\text{miss}}$ measurement (the use of calorimeter cluster information is used in the cuts for misreconstructed tracks). It should also be noted that very high $\mathbf{p}_T$ electron tracks are checked for poorly reconstructed momentum, and in the case that an electron track fails these checks, the electron cluster momentum is used in place of the track $\mathbf{p}_T$.

Tau leptons and heavy flavour-tagged jets are not explicitly taken into account in a separate term (though the ATLAS reconstruction software does make provision for them), but are included nevertheless to a certain degree. Three-prong hadronically decaying taus will be reconstructed as a jet

and included in the jet term, and 1-prong decays will either be reconstructed as an electron or a jet depending on the hadronic fraction. Particles resulting from b-tagged jets end up mostly in the soft term, and despite their displaced vertex still pass the d_0 and z_0 cuts (validated in the $\text{VH} \rightarrow b\bar{b}$ analysis).

4.4.2 Object-corrected $\mathbf{p}_T^{\text{miss}}$

While the nominal approach provides a measurement that, unlike the calorimeter, is mostly insensitive to pileup, it suffers from its own limitations, such as a (in certain cases, non-negligible) fraction of the momentum lost per event owing to the non-measurement of neutral particles, electron bremsstrahlung, and limited η coverage, and poor track resolution at very high $\mathbf{p}_T$. To counter such effects, we can replace the track-based terms containing the associated tracks for each high $\mathbf{p}_T$ object with their reconstructed and fully calibrated momentum counterpart. For leptons this means replacing the $\mathbf{p}_T$ of their associated ID track with the calorimeter-measured transverse energy (electrons), or the combined ID + MS fitted momentum (muons). For electrons, this allows us to recover their full $\mathbf{E}_T$ without any radiation loss, while for muons the combined muon momentum reconstructed using both the ATLAS ID and MS is generally more accurate. In the case of jets, by replacing the set of ghost-associated tracks with the fully calibrated $\mathbf{p}_T$ of each jet (as described in section 4.3.3), we recover both the neutral component of each jet as well as the full $\mathbf{p}_T$ of jets that are reconstructed in the forward region ($|\eta| > 2.5$). The soft track term remains as-is, however, and the reconstructed object-corrected $\mathbf{p}_T^{\text{miss}}$ is therefore:

$$\mathbf{p}_{x,y}^{\text{miss,object}} = - \left(\sum_{\text{electron object}} \mathbf{p}_{x,y} + \sum_{\text{muon object}} \mathbf{p}_{x,y} + \sum_{\text{jet object}} \mathbf{p}_{x,y} + \sum_{\text{soft tracks}} \mathbf{p}_{x,y} \right) \quad (4.4)$$

$$\Sigma \mathbf{p}_T^{\text{object}} = \sum_{\text{electron object}} \mathbf{p}_T + \sum_{\text{muon object}} \mathbf{p}_T + \sum_{\text{jet object}} \mathbf{p}_T + \sum_{\text{soft tracks}} \mathbf{p}_T \quad (4.5)$$

with:

$$\mathbf{p}_T^{\text{miss,object}} = \sqrt{\left(\mathbf{p}_x^{\text{miss,object}}\right)^2 + \left(\mathbf{p}_y^{\text{miss,object}}\right)^2} \quad (4.6)$$

The nominal and object-corrected calculations of the $\mathbf{p}_T^{\text{miss}}$ extend our arsenal of tools for use in physics analyses by providing complementary measurements of the missing transverse momentum in the recorded events, and together have provided useful insights into the underlying physics mechanisms of the LHC collisions. A discussion of the performance of the $\mathbf{p}_T^{\text{miss}}$ algorithms for various event topologies follows in chapter 5, and its use in Run 1 physics analyses is covered in chapter 6.

4.5 $\mathbf{E}_T^{\text{miss}}$ Reconstruction

Incoming particles usually deposit their energy both laterally and longitudinally in many calorimeter cells. The ATLAS reconstruction software uses clustering algorithms to group the cells and sum the total energy deposited within each cluster. These energies are then calibrated according to particle type, accounting for the energy deposited outside the cluster and in dead material nearby [62, 63]. Two types of clustering algorithms are used [64]: a “sliding window” algorithm that sums cells within a fixed rectangular size to efficiently and precisely reconstruct electromagnetically interacting particles and narrow jets from tau lepton decays; and a topological method which clusters neighbouring cells that have a significant signal to noise ratio. These “topoclusters” therefore have a variable number of cells, and are used for jet and $\mathbf{E}_T^{\text{miss}}$ reconstruction.

The $\mathbf{E}_T^{\text{miss}}$ reconstruction algorithm is described in detail in [65, 66]. It uses information from all the reconstructed and calibrated physics objects, associating calorimeter energy deposits with high $\mathbf{p}_T$ objects in a well-defined order⁶, and creating an $\mathbf{E}_T^{\text{miss}}$ term for each object type from their negative vectorial sum. The muon term uses the information from the Muon Spectrometer as muons typically leave minimal energy in the calorimeter.⁷ Topoclusters not associated with any objects are also taken into account, grouped into an $\mathbf{E}_T^{\text{miss}}$ “soft” term.⁸

The total $\mathbf{E}_T^{\text{miss}}$ is therefore the vectorial sum of these terms:

$$\mathbf{E}_{x,y}^{\text{miss}} = \mathbf{E}_{x,y}^{\text{miss}, e} + \mathbf{E}_{x,y}^{\text{miss}, \gamma} + \mathbf{E}_{x,y}^{\text{miss}, \tau_{had}} + \mathbf{E}_{x,y}^{\text{miss}, jets} + \mathbf{E}_{x,y}^{\text{miss}, \mu} + \mathbf{E}_{x,y}^{\text{miss}, soft\ term} \quad (4.7)$$

⁶Electrons, photons, hadronically-decaying tau leptons, jets, and finally muons.

⁷Any muon energy loss in the calorimeters is subtracted from the $\mathbf{E}_T^{\text{miss}}$ to avoid double counting the energy.

⁸The soft term includes contributions from both low $\mathbf{p}_T$ (<20 GeV) jets, and unassociated topoclusters.

with

$$\mathbf{E}_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \quad (4.8)$$

and its magnitude and direction is used in a number of physics analyses. Another often-used quantity for parametrisation and event classification is the total transverse energy of the event, defined by the scalar sum of the same components:

$$\Sigma E_T = \sum E_T^e + \sum E_T^\gamma + \sum E_T^{\tau_{had}} + \sum E_T^{jets} + \sum p_T^\mu + \sum E_T^{soft \ term} \quad (4.9)$$

Chapter 5

$\mathbf{p_T^{miss}}$ Performance in $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ Events from $\sqrt{s} = 8$ TeV pp Collisions

The relatively abundant production of W and Z bosons at the LHC and their subsequent leptonic decays provide clear experimental signatures that are not only used for precision electroweak measurements and tests of QCD processes, but also are important backgrounds in a number of new physics searches. Having generally well-understood topologies, these events also act as standard candles against which we can measure the performance of our detector and reconstruction algorithms. In the $Z \rightarrow \ell\ell$ case, the absence of real $\mathbf{E_T^{miss}}$ in the event allows us to measure the intrinsic resolution and performance of the $\mathbf{p_T^{miss}}$ that results mainly from detector response and object reconstruction efficiencies. By categorising the events by the number of jets produced in association with the Z boson, we can also gain a measure of the performance that is related to the underlying QCD processes in the event. In the $W \rightarrow \ell\nu$ channel, the neutrino provides a good metric against which to measure the $\mathbf{p_T^{miss}}$ scale and direction, and we can again categorise the events based on the number of associated jets, as well as the $\mathbf{p_T}$ of the reconstructed W boson.

In this chapter, we first briefly discuss the $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ event selection, and then give a detailed account of the performance studies on the $\mathbf{p}_T^{\text{miss}}$ using these events, the developments of which were presented regularly at internal ATLAS subgroup meetings from late 2011 onwards. We present here the final results on the conclusive 2012 dataset, detailing the validation of the track-based method and its extensions, a comparison between the $\mathbf{p}_T^{\text{miss}}$ reconstructed using data and Monte Carlo simulated samples, and performance studies on the resolution and scale of the $\mathbf{p}_T^{\text{miss}}$.

5.1 Event Selections

The selection of $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ events follows the ATLAS general and Standard Model group recommendations, so that direct comparison and the use of the performance statistics in other ATLAS analyses is possible. Only events that fall within the “Good” run list as described in section 3.4 are used. In addition these events must have fired a single or a dilepton trigger (by “lepton” we mean electron or muon). Events are vetoed if they contain calorimeter noise bursts or jets over 20 GeV that are known to be badly reconstructed. For good vertex reconstruction, we also require that the primary vertex has at least three associated reconstructed tracks each with $p_T > 400$ MeV.

5.1.1 $Z \rightarrow \ell\ell$ event selection

For $Z \rightarrow \ell\ell$ events, a trigger on high $\mathbf{p}_T$ leptons was required. In the muon channel, the event triggered on one “tight” quality muon with a $\mathbf{p}_T$ greater than 24 or 36 GeV¹, whereas for the electron channel a trigger on two loose electrons with $\mathbf{p}_T$ greater than 12 GeV each was required. Leptons are selected as per those defined in section 4.3.2, with the additional requirement that their $\mathbf{p}_T$ is greater than 25 GeV. Muon tracks are also required to have both a minimum number of ID hits used for the track reconstruction, as well as a maximum displacement from the main primary vertex of 10 mm in the z direction (along the beamline) [55]. Additional isolation criteria are applied around the muon tracks.

¹The 24 GeV trigger imposes an isolation requirement on the muon based on ID tracks, whereas the 36 GeV one does not.

The final $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ selections require exactly two leptons with opposite charge, with one (or both, in the electron case) to be the lepton that fired the trigger. The combined invariant mass of the two leptons is calculated, and the event is selected as a candidate $Z \rightarrow \ell\ell$ event if this falls between 66 and 116 GeV (i.e. within $|M_{ll}| < 25$ GeV of the Z mass).

5.1.2 $W \rightarrow \ell\nu$ event selection

For the $W \rightarrow \ell\nu$ selection, a single lepton trigger was required for both electron and muon channels: the muon trigger was the same as above for the $Z \rightarrow \mu\mu$ events, while one medium isolated electron with $\mathbf{p}_T$ greater than 24 GeV or one medium electron (with no isolation requirement) of $\mathbf{p}_T$ greater than 60 GeV triggered the electron channel. Again, the lepton selection of section 4.3.2 with $\mathbf{p}_T > 25$ GeV is applied, though additional selections are required to pass the “tight” identification criteria and an isolation requirement, in order to reduce contamination from backgrounds. The additional quality requirements on the muon track and isolation described above for the Z case also apply for the W . Exactly one selected, trigger-matched lepton is allowed in the event, and the $\mathbf{E}_T^{\text{miss}}$ measured by the calorimeter is required to be at least 30 GeV.

In the context of $W \rightarrow \ell\nu$ events the $\mathbf{E}_T^{\text{miss}}$ is used as a measure of the neutrino momentum. The reconstructed transverse mass of the lepton- $\mathbf{E}_T^{\text{miss}}$ system is therefore calculated using:

$$m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos \phi)} \quad (5.1)$$

where ϕ is the azimuthal angle between the lepton momentum (p_T^ℓ) and $\mathbf{E}_T^{\text{miss}}$ directions. For the event to pass as a candidate $W \rightarrow \ell\nu$ event, this reconstructed transverse mass is required to be greater than 50 GeV.

5.1.3 $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ event backgrounds

While the W and Z boson leptonic decays do provide clear experimental signatures within the detector, a number of other processes from the pp scattering practically contribute to their cross

section as backgrounds by mimicking their signature. Although a strict set of event selections is applied to the data to minimise these contributions, some processes are non-negligible and so need to be taken into account.

In $Z \rightarrow \ell\ell$ events, where our signal is two same-flavour leptons, the most apparent backgrounds come from diboson and $t\bar{t}$ production, and from Z boson decays to two τ leptons. The relevant fractions of the different backgrounds depend on the event topology: for example, in events with no additional hard jets, the primary background comes from the $Z \rightarrow \tau\tau$ decays, where the τ leptons decay to leptons of the same flavour. In events with associated jets, diboson production makes more of a contribution. With ZZ production, one Z decaying leptonically could pass our selections, while the other Z may decay invisibly, to hadrons (appearing as two jets in the detector), or to leptons whose trajectories fall outside of the detector acceptance or do not pass our quality selections. For WZ events, the extra lepton from the W decay may either fall outside of our detector, or be misreconstructed as a jet or photon (particularly in the electron case), leaving us once again with detecting just a single Z. And for WW production, the subsequent leptonic decay of the W bosons yields two leptons which may together mimic the Z decay signal. With the high collision energy of the LHC, the cross section for top quark pair production (denoted σ_t in figure 2.5) is of an order that is close to that of the signal process. The top quarks decay with an almost 100% branching ratio to a W boson and a b quark, and the subsequent decays of the W and b quark could present again as leptons and jets in the detector, especially for events with a high jet multiplicity.²

In $W \rightarrow \ell\nu$ events, in addition to the processes mentioned above, $Z \rightarrow \ell\ell$ and $W \rightarrow \tau\nu$ events also contribute to the background, where our signal is a single lepton plus missing transverse momentum in the detector. $Z \rightarrow \ell\ell$ events may fake this if one of the leptons is either misreconstructed as a jet or photon, or falls outside the detector acceptance, and $W \rightarrow \tau\nu$ events contribute when the tau decays hadronically. And in this case, $Z \rightarrow \tau\tau$ events would contribute when one tau decays leptonically, while the other decays hadronically and is mistaken for a regular jet (or both decay leptonically, but we “lose” one lepton out of acceptance). Similar arguments as above apply to the diboson backgrounds, though in this case the processes involving W bosons have a higher likelihood

²The b quark decays to a lighter c quark and a W boson, and the W boson subsequently decays either leptonically or hadronically. The two leptons could then come from the leptonic decays of any of the W bosons in the process, and the number of jets in the event would depend on the number of hadronic decays.

of contributing than those containing a Z. For $t\bar{t}$ events, all we need is one leptonic decay of one of the W bosons involved, and we have a candidate W-plus-multiple-jets event.

Finally, the overwhelming cross section for QCD processes may contribute as backgrounds if one or two high momentum leptons from other vertices are also produced in the event, or if the jets are misreconstructed as electrons. The likelihood of selecting two same-flavour leptons this way is incredibly small, so this background is negligible in $Z \rightarrow \ell\ell$ events. A single additional lepton in the event, however, is indeed feasible, especially with the large number of pileup vertices in the event, and so QCD produces a significant background in $W \rightarrow \ell\nu$ events.

5.2 Overview of the $\mathbf{p}_T^{\text{miss}}$ Distributions

Before more detailed studies are considered, we ought to ensure that we fully understand our $\mathbf{p}_T^{\text{miss}}$ algorithm and its various features with respect to the events being considered. This covers the basic distributions, as well as variations when considering different event topologies, such as the decays with different lepton flavours, and number of jets in the event.

5.2.1 Basic nominal $\mathbf{p}_T^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$ events

We start with the most standard of the event configurations, $Z \rightarrow \mu\mu$. The physics underlying Z boson production is generally well understood, and the two high $\mathbf{p}_T$ muons in the signal are well reconstructed by the ATLAS combined reconstruction software. By comparing both the 0 jet and inclusive channel we are also able to probe the performance of our algorithm for events with different underlying QCD processes. In these events, where there is no real $\mathbf{E}_T^{\text{miss}}$, we expect no net reconstructed missing transverse momentum, neither calorimeter- nor track-based. Therefore we expect peaks around 0 in the distributions for the x , y , and transverse components, with the resolution of the peak indicating the sensitivity of the reconstruction.

Figure 5.1 shows a comparison between the x and y component distributions, in data and signal Monte Carlo simulation, for both the nominal $\mathbf{p}_T^{\text{miss}}$ and calorimeter-based $\mathbf{E}_T^{\text{miss}}$, for the inclusive

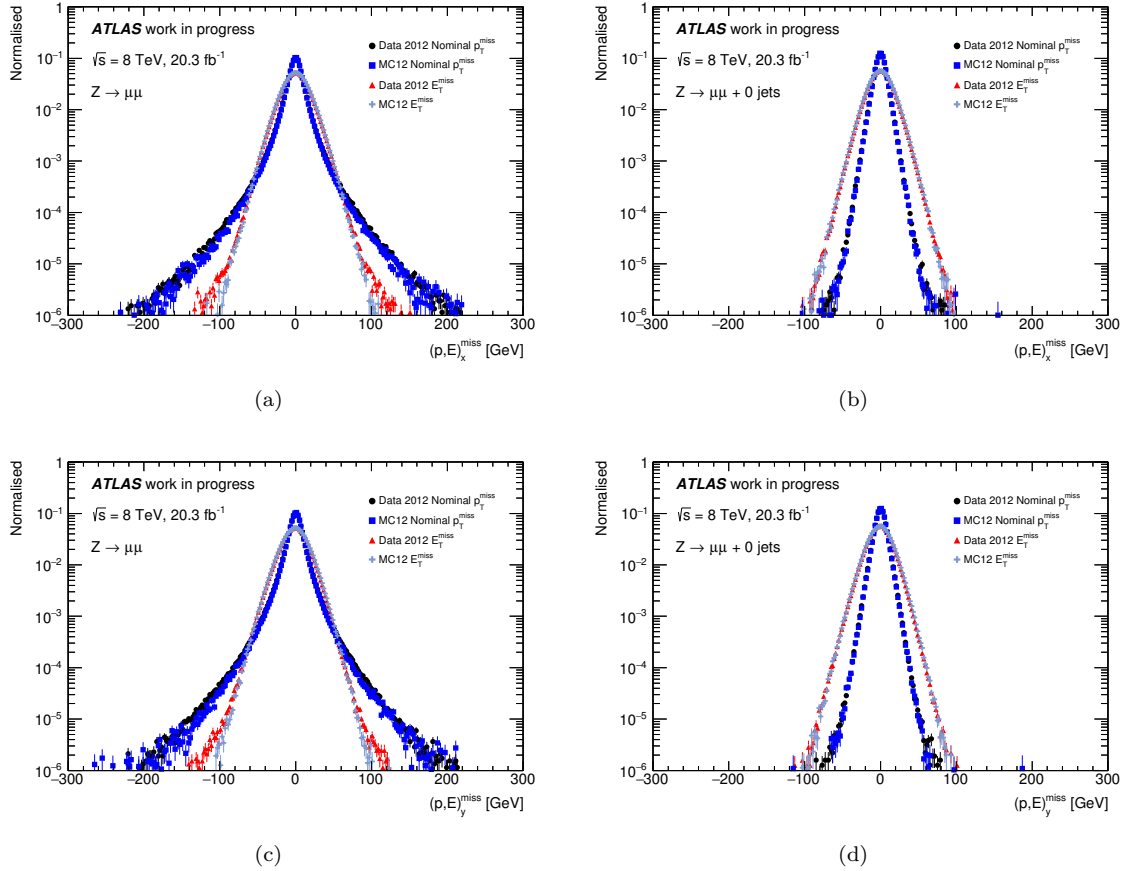


Figure 5.1: x (top) and y (bottom) components of the nominal $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ in $Z \rightarrow \mu\mu$ inclusive (left) and 0 jet (right) events.

(left) and 0-jet (right) cases.³ As expected, we see a peak centred around 0 for both the $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ distributions, symmetric in x and y which indicates a good alignment of the detector. At the core, the $\mathbf{p}_T^{\text{miss}}$ provides a narrower peak, showing the better precision of the $\mathbf{p}_T^{\text{miss}}$ in events with no real $\mathbf{E}_T^{\text{miss}}$ (since the $\mathbf{E}_T^{\text{miss}}$ is smeared by other non-primary-vertex based contributions), and indeed performs better overall for 0-jet events. However, in inclusive events the $\mathbf{p}_T^{\text{miss}}$ has longer tails as a result of the missing neutral component from the jets in the event, which provides a fake $\mathbf{p}_T^{\text{miss}}$ and broadens the distribution.⁴ Finally, overall we see good agreement between the 2012 data and the simulated signal samples. The values of the mean and RMS of each of the distributions in figure 5.1 are summarised in table 5.1 below.

³Here we require 0 jets in both the track- and calorimetric-based reconstructions.

⁴The inclusive case is still dominated by 0-jet events, which is why the $\mathbf{p}_T^{\text{miss}}$ performs well in the core.

Table 5.1: $\mathbf{p}_x^{\text{miss}}$ and $\mathbf{p}_y^{\text{miss}}$ mean and RMS values in $Z \rightarrow \mu\mu$ Data and signal Monte Carlo

$Z \rightarrow \mu\mu$		Inclusive		0 jet	
		Mean [GeV]	RMS [GeV]	Mean [GeV]	RMS [GeV]
Nominal $\mathbf{p}_x^{\text{miss}}$	Data	-0.083	13.72	-0.056	7.896
Nominal $\mathbf{p}_x^{\text{miss}}$	MC	-0.047	13.00	-0.028	7.753
$\mathbf{E}_x^{\text{miss}}$	Data	0.093	16.68	0.056	15.17
$\mathbf{E}_x^{\text{miss}}$	MC	0.130	16.73	0.086	15.35
Nominal $\mathbf{p}_y^{\text{miss}}$	Data	0.104	13.78	0.161	7.919
Nominal $\mathbf{p}_y^{\text{miss}}$	MC	0.090	13.05	0.151	7.755
$\mathbf{E}_y^{\text{miss}}$	Data	-1.148	16.70	-0.937	15.17
$\mathbf{E}_y^{\text{miss}}$	MC	-0.926	16.80	-0.739	15.41

The missing transverse energy or momentum distributions are calculated from the vectorial sum of the x and y components, and these distributions are shown in figure 5.2. Here, both $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ events are shown, so we can see the effect of real $\mathbf{E}_T^{\text{miss}}$ on the distributions. For the $Z \rightarrow \mu\mu$ events (top), since the overall event has no real $\mathbf{E}_T^{\text{miss}}$ we expect a narrow peak close to 0, with a tail originating from fake $\mathbf{E}_T^{\text{miss}}$ or $\mathbf{p}_T^{\text{miss}}$ signals. Indeed this is seen, with the core of the $\mathbf{p}_T^{\text{miss}}$ distribution closer to 0 than that of the $\mathbf{E}_T^{\text{miss}}$, while the $\mathbf{p}_T^{\text{miss}}$ tail is longer in events with jets. Because only the signal Monte Carlo sample is used, the tail in the data is larger; the rest of the contribution comes from background events faking $\mathbf{E}_T^{\text{miss}}$ and increasing the tail (Plots including the full backgrounds will be shown in section 5.3). The deviation of the mean from 0 is also expected, since the $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ are reconstructed quantities dependent on detector acceptance and resolution, the reconstruction efficiency of the reconstruction algorithms, and - in the $\mathbf{E}_T^{\text{miss}}$ case - contributions from pileup events. In comparison, the shift in the peak is shown for the $W \rightarrow \mu\nu$ events (bottom) where real $\mathbf{E}_T^{\text{miss}}$ is present owing to the neutrino from the W boson decay, though the source of the tails remains the same for these events.

Another useful quantity to consider is the scalar sum of each of the components of the $\mathbf{E}_T^{\text{miss}}$ or $\mathbf{p}_T^{\text{miss}}$, ΣE_T and Σp_T respectively, and this is shown in figure 5.3, again for both $W \rightarrow \mu\nu$ and $Z \rightarrow \mu\mu$ events. The similarity in the ΣE_T distributions show that the overall event activity has almost the same scale for both W and Z boson production. However, the absence of the neutrino is noted in the lower-shifted Σp_T distributions, an effect which is mostly washed out in the $\mathbf{E}_T^{\text{miss}}$

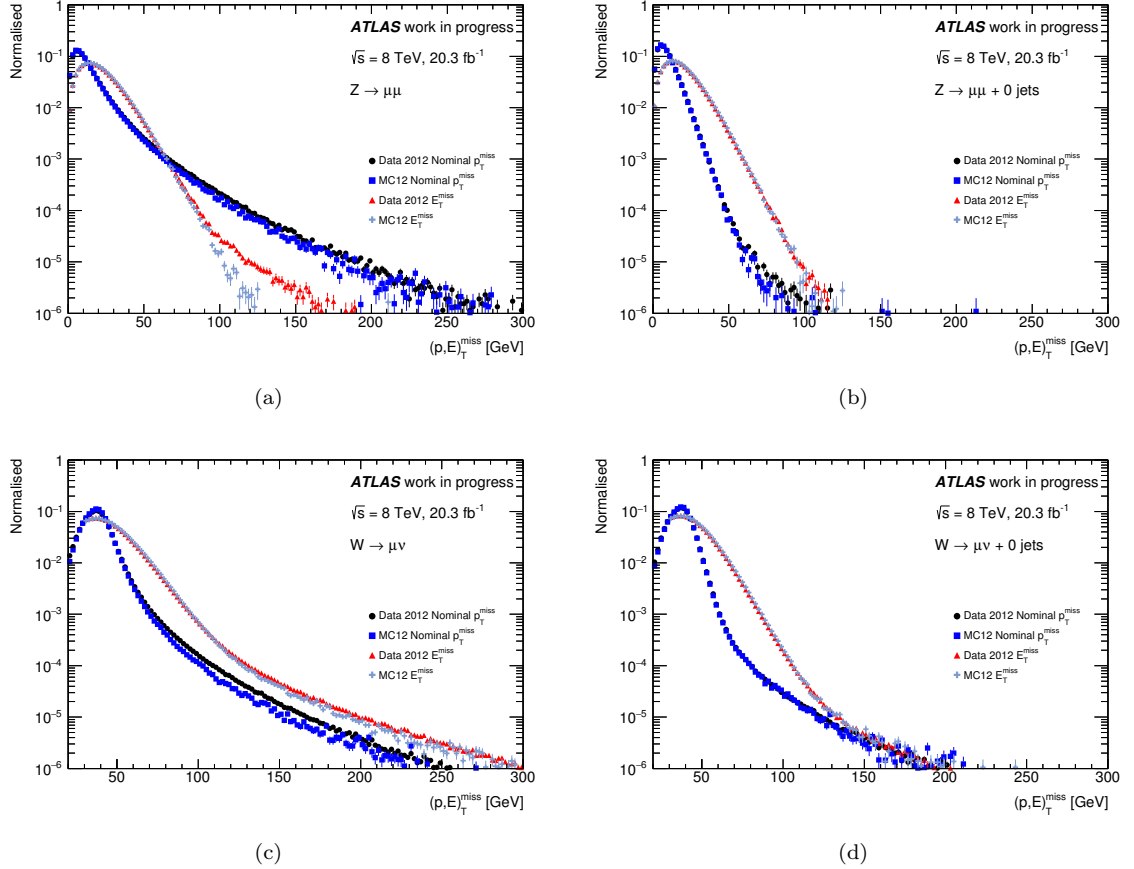


Figure 5.2: Nominal $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$ (top) and $W \rightarrow \mu\nu$ (bottom) inclusive (left) and 0 jet (right) events.

owing to the large extra contributing activity from pileup events, and which indicates the greater sensitivity of the $\mathbf{p}_T^{\text{miss}}$ for probing just the primary interaction.

5.2.2 $\mathbf{p}_T^{\text{miss}}$ in the muon and electron channels

In the electron decay channels, an extra effect on the $\mathbf{p}_T^{\text{miss}}$ is introduced during the reconstruction when we consider the Bremsstrahlung radiation of electrons inside the inner detector. The result of this is a mismeasured (mostly lower) electron track $\mathbf{p}_T$ when compared to the corresponding calorimeter-measured $\mathbf{p}_T$ from the electron reconstruction algorithm, an effect which produces an additional (fake) contribution to the $\mathbf{p}_T^{\text{miss}}$. This is clearly shown in figure 5.4, which compares the $\mathbf{p}_T^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events; for the nominal $\mathbf{p}_T^{\text{miss}}$ distributions a clear

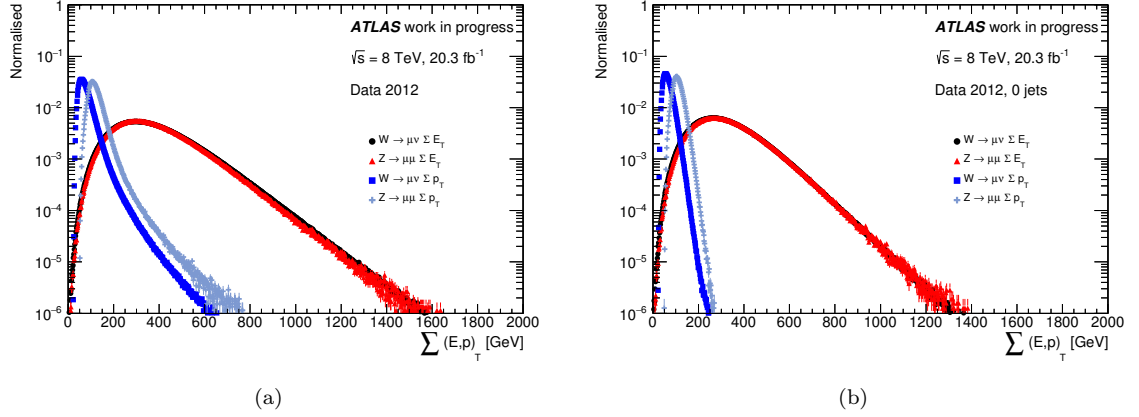


Figure 5.3: Scalar ΣE_T and Σp_T distributions for inclusive (a) and 0 jet (b) $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ events.

broadening of the peak is visible in the electron channel owing to this effect (the same effect in the 0 jet channel indicates that the effect does not stem from any jet-related effect). To compensate for this and to recover the lost momentum owing to Bremsstrahlung, we replace the electron track momentum with the momentum calculated from the electron cluster energy measured by the calorimeter and the electron track direction⁵ for all electrons in the event. When this is done we can see that the resulting $\mathbf{p}_T^{\text{miss}}$ distribution for the electron “cluster corrected” channel matches that of the muon channel well.

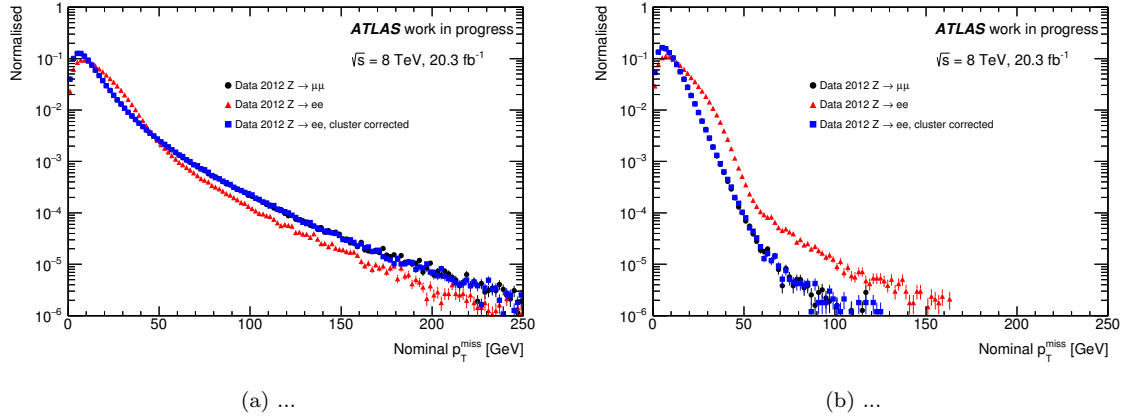


Figure 5.4: Comparison between the nominal $\mathbf{p}_T^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ inclusive (a) and 0 jet (b) events. The difference in the distributions is due to momentum loss from electron Bremsstrahlung which is not well considered in the nominal case. When this momentum is correctly taken into account, as shown in the “cluster-corrected” distributions, the muon and electron channels are well matched.

⁵We use the track η, ϕ as it has better sensitivity than the cluster η, ϕ .

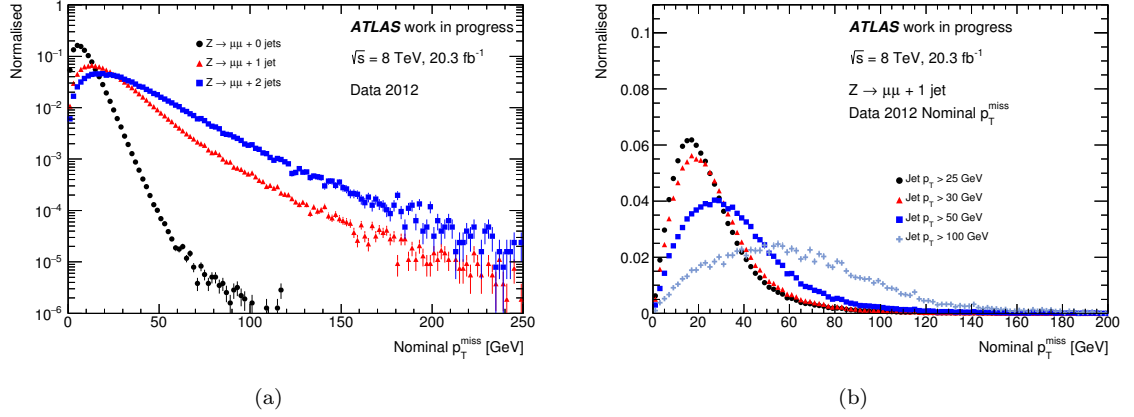


Figure 5.5: Effect of the number of jets (a) and the jet $\mathbf{p}_T$ (b) on the nominal $\mathbf{p}_T^{\text{miss}}$ distributions for $Z \rightarrow \mu\mu$ events. The broadening of the distribution is due to the lost momentum carried by the neutral component of the jet(s), which is affected by both the number of jets and the total $\mathbf{p}_T$ of the jet.

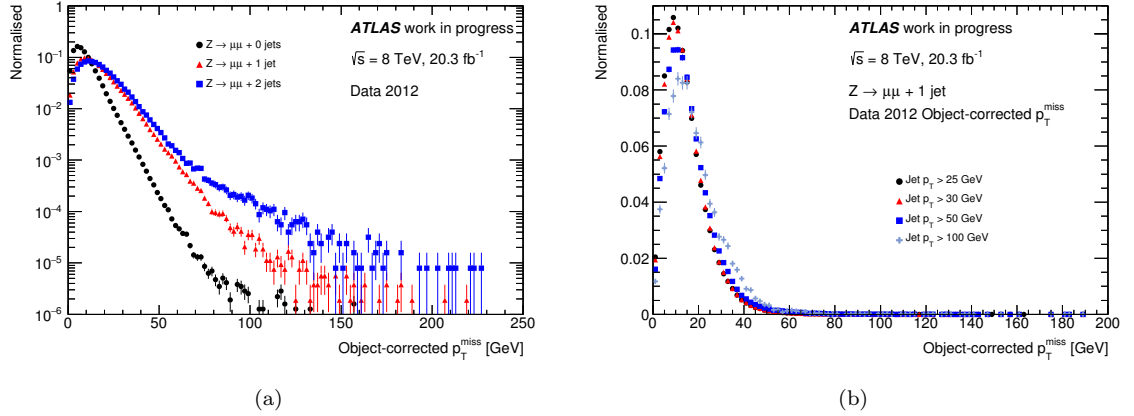


Figure 5.6: Effect of the number of jets (a) and the jet $\mathbf{p}_T$ (b) on the object-corrected $\mathbf{p}_T^{\text{miss}}$ distributions for $Z \rightarrow \mu\mu$ events. The difference in the distributions between events with different jet multiplicities is reduced, and the effect of the jet $\mathbf{p}_T$ in 1 jet events is almost negligible.

5.2.3 The effect of jets in the event

The difference in the $\mathbf{p}_T^{\text{miss}}$ distribution for 0 jet and inclusive events is noticeable, with the $\mathbf{p}_T^{\text{miss}}$ performance worsening with the number of jets in the event, as well as with the jet $\mathbf{p}_T$. There are two reasons for this: first, jets contain a large component ($\sim 40\%$) of neutral particles which do not leave tracks in the inner detector, and second, jets may be emitted with large forward angles, outside the range of our tracking detector.⁶ In the first case, a significant fraction of the jet $\mathbf{p}_T$ is

⁶Recall we select jets with an acceptance up to $|\eta| < 4.4$, while the ID only extends to $|\eta| < 2.5$.

lost, and in the second, the entire jet's contribution is not considered, both of which contribute to a large amount of fake $\mathbf{p}_T^{\text{miss}}$ in the event. This is shown in figure 5.5 (a), with the broadening of the $\mathbf{p}_T^{\text{miss}}$ distribution and a shifting of the peak as the total number of jets in the event increases, and - to specifically show the contribution from the missing neutrals without any acceptance effects - for events with 1 central jet for various values of the jet $\mathbf{p}_T$ (b). (For the $Z + 1$ central jet events, the Z boson and the single jet were both required to be within $|\eta_{Z,jet}| < 2.0$ to ensure full coverage of both the hard and underlying event activity within the limits of the ID.⁷) The result of missing the neutral particles on the scale of the $\mathbf{p}_T^{\text{miss}}$ measurement is discussed in detail in section 5.5 and figure 5.24.

5.2.4 The object-corrected $\mathbf{p}_T^{\text{miss}}$

It was as a result of these two factors - the electron Bremsstrahlung and the effect of jets in the event - that the object-corrected version of the $\mathbf{p}_T^{\text{miss}}$ was developed, a method to recover the full contributions from the hard $\mathbf{p}_T$ objects in the event that were unable to be completely taken into account by using only the tracking detector. Figure 5.6 shows the same two plots as figure 5.5, with the object-corrected $\mathbf{p}_T^{\text{miss}}$ instead. We can see a reduced dependence on the number of jets (a), and a greatly reduced dependence on the jet $\mathbf{p}_T$ when the jet is central (b). Of course, the distributions in figure 5.6 (a) are not identical, a consequence of the limited acceptance of the ID (even if we include a forward jet, there may be hadronic recoil activity in the opposite forward direction that we do not include), as well as the jet reconstruction, calibration and selection.

The jet selection criteria were discussed in section 4.3.3 and follow the general ATLAS guidelines for good and inclusive jet selection while maintaining an efficient rejection of jets from QCD background and other pileup processes. The selection is by no means infallible, however, and this shows up particularly for primary-vertex-based quantities such as the $\mathbf{p}_T^{\text{miss}}$. Figure 5.7 shows the difference between the true $\mathbf{E}_T^{\text{miss}}$ and the reconstructed $\mathbf{p}_T^{\text{miss}}$ in $Z \rightarrow \mu\mu$ plus 1 jet events, where the jet is either central (a) or forward (b).⁸ The central jet event selection is as applied above, and for the forward jet selection we require that the Z and jet $\mathbf{p}_T$ fall completely outside the tracking acceptance

⁷Although the ID extends to $|\eta| < 2.5$, we use the additional restriction here to ensure that the ID completely covers jets of cone size 0.4.

⁸The true $\mathbf{E}_T^{\text{miss}}$ is calculated from all the noninteracting final-state truth particles in an event on Monte Carlo.

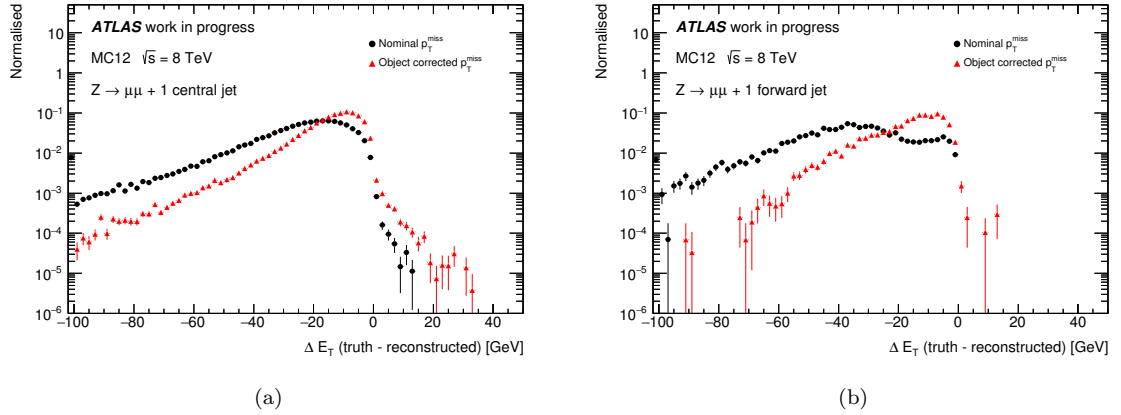


Figure 5.7: Difference between the true $\mathbf{E}_T^{\text{miss}}$ and reconstructed $\mathbf{p}_T^{\text{miss}}$ in $Z \rightarrow \mu\mu + 1$ jet events, where the jet is either central (a) or forward (b).

(i.e. $|\eta_{Z,jet}| > 3.0$) with the additional requirement that the Z and the jet be back-to-back so that most of the out of acceptance momentum for the event is contained in the jet.

The plots in figure 5.7 show both the nominal $\mathbf{p}_T^{\text{miss}}$, as well as the object corrected $\mathbf{p}_T^{\text{miss}}$, and in the central jet case (a) we can clearly see the improvement in the object-corrected $\mathbf{p}_T^{\text{miss}}$ distribution when the jet is added. In the forward jet case, however, we see a small central peak in the nominal distribution in addition to the broadening, as well as a shoulder in the object corrected $\mathbf{p}_T^{\text{miss}}$. The reason for this is that (despite the higher $\mathbf{p}_T$ cut in the forward region) the jet selection is tighter for jets in the central region owing to the availability of tracks and, hence, the cut on the jet vertex fraction. In the forward region there is no vertex-matching ability on the jet, and as a result the jet is more likely to be a result of pileup. The higher $\mathbf{p}_T$ cut here mitigates this somewhat, but there is still a risk of including a jet from a pileup vertex in the object-corrected $\mathbf{p}_T^{\text{miss}}$, introducing fake $\mathbf{p}_T^{\text{miss}}$ - and hence the shoulder - to the calculation.

This can be more clearly seen in the two-dimensional distributions in figure 5.8 where we show the same ΔE_T distributions as in figure 5.7 but as a function of the transverse momentum of the Z boson $\mathbf{p}_T^Z$. For the central jet case (left), we can see the single, offset peak of the nominal $\mathbf{p}_T^{\text{miss}}$ (a) and its obvious improvement towards 0 when the jet $\mathbf{p}_T$ is added; we can have confidence that this is a true Z + 1 jet event because the peak in the distribution is at a value of $\mathbf{p}_T^Z$ that balances that of the selected jet. However, in the forward jet case (right), we see the two peaks in the nominal $\mathbf{p}_T^{\text{miss}}$ distribution (b) at different values of $\mathbf{p}_T^Z$: the peak near 0 for low values of $\mathbf{p}_T^Z$ indicates that these

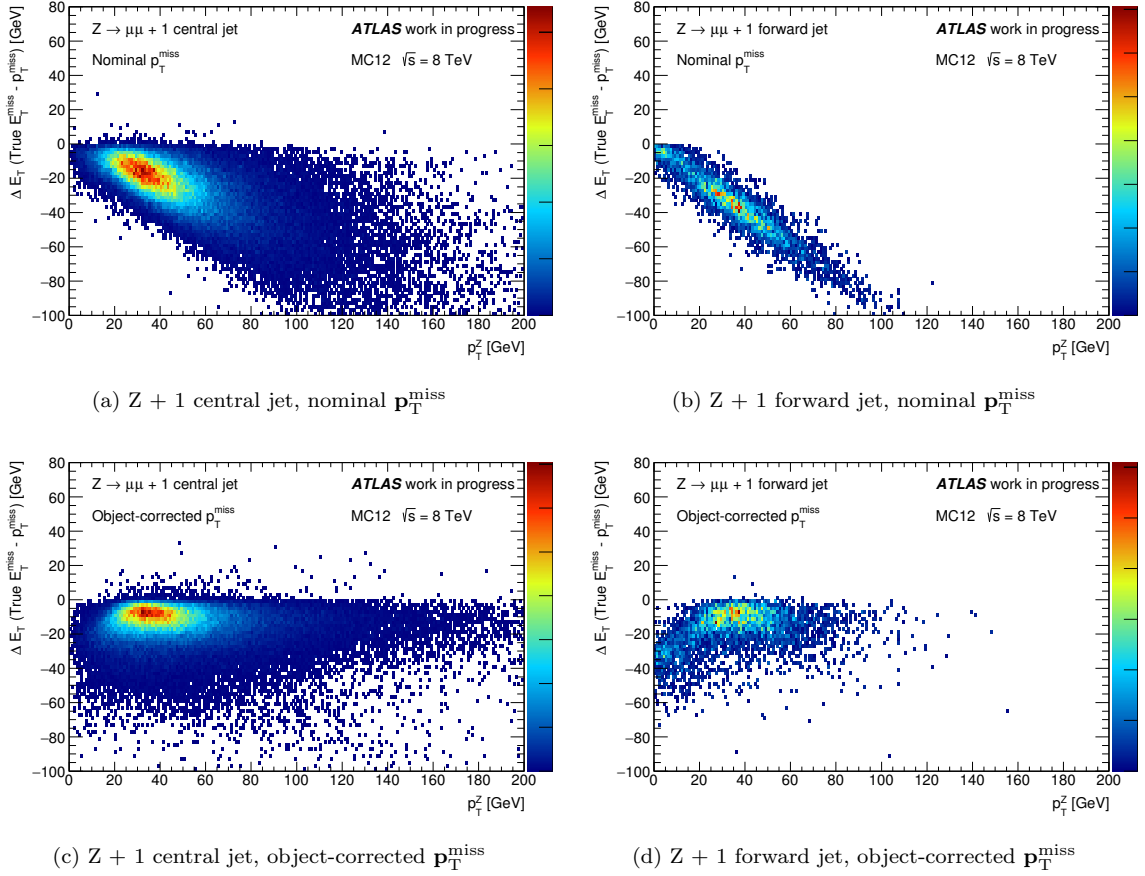


Figure 5.8: Difference between the true $\mathbf{E}_T^{\text{miss}}$ and reconstructed $\mathbf{p}_T^{\text{miss}}$ as a function of the transverse momentum of the Z boson, in $Z \rightarrow \mu\mu + 1$ jet events, where the jet is either central (left) or forward (right). Both nominal (top) and object-corrected (bottom) $\mathbf{p}_T^{\text{miss}}$ distributions are shown. For the central jet case, the improvement to the $\mathbf{p}_T^{\text{miss}}$ distribution when moving from the nominal (a) to object-corrected (c) methods is clear. In the forward jet case when one includes the jet (d), one can see the double peak corresponding to the jet originating from a pileup vertex (for low values of $\mathbf{p}_T^Z$) and from the signal vertex (for $\mathbf{p}_T^Z \sim 30$ GeV.)

are most likely 0 jet events, and the extra jet selected in the forward region most likely originates from one of the pileup vertices. This translates to an offset from 0 in the object corrected $\mathbf{p}_T^{\text{miss}}$ distribution (d) for the same low values of $\mathbf{p}_T^Z$. Alternatively, the offset peak in the nominal $\mathbf{p}_T^{\text{miss}}$ distribution around $\mathbf{p}_T^Z \sim 30$ GeV corresponds to true Z + 1 forward jet events where the jet now does come from the signal vertex, with the result that the object corrected $\mathbf{p}_T^{\text{miss}}$ is now close to 0.

Similar distributions were obtained for the Z + 2 jet case, comparing the cases where the two jets are both central (figure 5.9 (a)), one central one forward (figure 5.9 (b)), and both forward (not shown due to lack of statistics), and similar arguments with respect to the jet selections hold here.

Therefore, the object-corrected $\mathbf{p}_T^{\text{miss}}$ with the full $\mathbf{p}_T$ of jets and electrons in the event improves the tails and resolution of the distributions with respect to the nominal $\mathbf{p}_T^{\text{miss}}$, as long as one takes care with the jet selection.

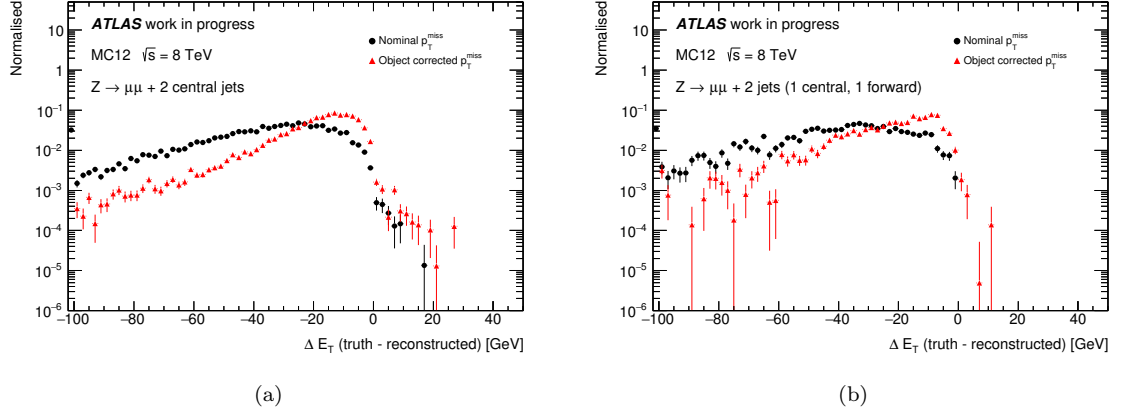


Figure 5.9: Difference between the true $\mathbf{E}_T^{\text{miss}}$ and reconstructed $\mathbf{p}_T^{\text{miss}}$ in $Z \rightarrow \mu\mu + 2$ jet events, where the jets are either both central (a), or one central, one forward (b) (the two forward jet case is not shown due to lack of statistics).

A comparison between the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ distributions for inclusive and 0 jet $Z \rightarrow \mu\mu$ events is shown in figure 5.10, and we can see the improvement in the tail of the $\mathbf{p}_T^{\text{miss}}$ distribution in the inclusive case when the jets are properly taken into account. Again, the difference between the data and Monte Carlo distributions in the tail is a result of additional backgrounds, as the signal-only Monte Carlo sample does not fully take these into account (see the next section). Finally, the values of the mean and RMS for the distributions in figure 5.10, as well as the $\mathbf{E}_T^{\text{miss}}$ shown in figure 5.2 (a) and (b), are summarised in table 5.2.

Table 5.2: $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ mean and RMS values in $Z \rightarrow \mu\mu$ Data and signal Monte Carlo

$Z \rightarrow \mu\mu$	Inclusive		0 jet	
	Mean [GeV]	RMS [GeV]	Mean [GeV]	RMS [GeV]
Nominal $\mathbf{p}_T^{\text{miss}}$ Data	13.68	13.75	9.260	6.245
Nominal $\mathbf{p}_T^{\text{miss}}$ MC	13.14	12.91	9.089	6.137
Object-corrected $\mathbf{p}_T^{\text{miss}}$ Data	12.17	9.769	9.465	6.733
Object-corrected $\mathbf{p}_T^{\text{miss}}$ MC	11.78	9.275	9.310	6.642
$\mathbf{E}_T^{\text{miss}}$ Data	20.21	12.25	18.47	10.95
$\mathbf{E}_T^{\text{miss}}$ MC	20.41	12.10	18.75	11.05

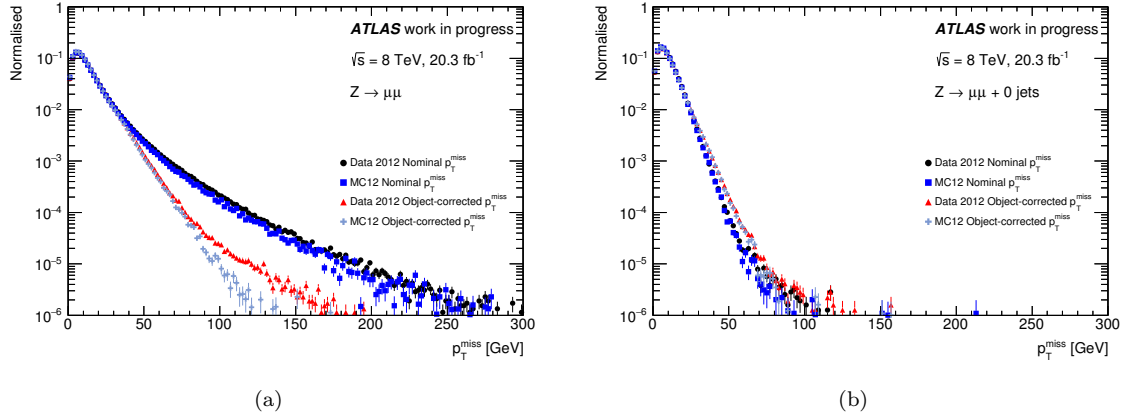


Figure 5.10: Nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$ inclusive (a) and 0 jet (b) events.

5.2.5 Correlation between $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$

The track-based $\mathbf{p}_T^{\text{miss}}$ provides a separate but complementary measure of the hard event that can be used independently or in conjunction with the calorimeter-based $\mathbf{E}_T^{\text{miss}}$ in analyses. Particularly, the relationship between the azimuthal directions of the $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ provides a useful variable one can use to separate events with true $\mathbf{E}_T^{\text{miss}}$ from fake backgrounds.

In Z boson events where there is no real $\mathbf{E}_T^{\text{miss}}$, we expect the reconstructed $\mathbf{E}_T^{\text{miss}}$ or $\mathbf{p}_T^{\text{miss}}$ to be randomly oriented around the azimuthal angle ϕ , with minimal correlation to one another. In W boson events, however, where there is real $\mathbf{E}_T^{\text{miss}}$ in the event, the neutrino provides a clearly defined direction along which the $\mathbf{E}_T^{\text{miss}}$ or $\mathbf{p}_T^{\text{miss}}$ should be oriented. For such events, a high degree of correlation between the two quantities is expected.

Figure 5.11 shows such a comparison: the $\Delta\phi$ distributions between the $\mathbf{E}_T^{\text{miss}}$ and the nominal or object-corrected $\mathbf{p}_T^{\text{miss}}$, for both $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ events, and we see the distributions as we would expect, with a much greater correlation for the events with real $\mathbf{E}_T^{\text{miss}}$. This feature has proven useful in various physics analyses such as the $H \rightarrow b\bar{b}$ search, where one uses a cut on the $\Delta\phi$ distribution to reject events with fake $\mathbf{E}_T^{\text{miss}}$ that may otherwise pass the event selections. Both the inclusive (a) and 1 jet (b) cases are shown here, particularly to note the interesting effect: while the object-corrected $\mathbf{p}_T^{\text{miss}}$ proves better in the overall distributions as we have seen above, and gives a

greater degree of correlation with the $\mathbf{E}_T^{\text{miss}}$ in W boson events, it also has an increased correlation in Z events - due in part to the fact that we now use calorimeter information in the algorithm. This serves to illustrate that the choice of $\mathbf{p}_T^{\text{miss}}$ algorithm for use in analyses is not a “one size fits all” approach with either the nominal or object-corrected versions being better; rather, the choice ought to be determined on a case-by-case basis, taking usage and event topology into account.

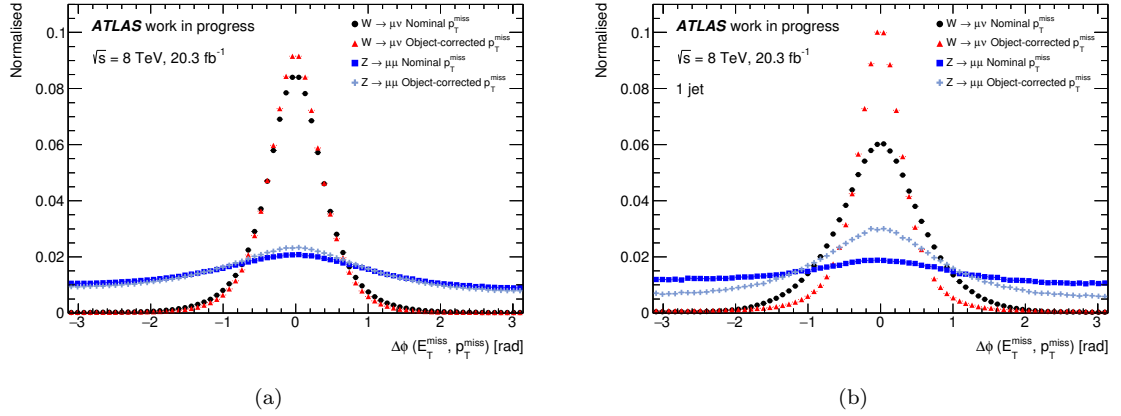


Figure 5.11: Difference $\Delta\phi$ between the azimuthal angles of the track-based $\mathbf{p}_T^{\text{miss}}$ and calorimeter-based $\mathbf{E}_T^{\text{miss}}$ for $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ inclusive (a) and 1 jet (b) events.

5.3 Comparison of $\mathbf{p}_T^{\text{miss}}$ Distributions in Data and Monte Carlo Simulation

For the most part, the Monte Carlo simulated signal samples shown in figures 5.1 and 5.2 above describe the data well. However, noticeable divergences between the data and simulation are seen, particularly in the tails of the distribution. This is because the selections we use for identifying Z and W boson events (while good) are not perfect, and contamination from the various backgrounds described in section 5.1.3 is inevitable. For a full comparison with the data, the samples simulating all the background processes need to be taken into account, with the correct weighting procedure for the relative cross sections and luminosity scaling applied. The full comparison is important, not only for determining the breadth of our understanding of the event at the truth level, but also in physics searches where cuts on the $\mathbf{p}_T^{\text{miss}}$ may be applied and discrepancies could worsen the systematic uncertainties for the analysis. Additionally, variations in the distributions with different event generators may indicate regions where one particular generator describes the event better than

another; indeed this is the case for the $\mathbf{p}_T^{\text{miss}}$, and a detailed comparison between data and samples generated with PowhegPythia vs AlpgenJimmy is given in appendix B. In the following plots we show only the distributions using AlpgenJimmy for the Z and W boson events (including the tau lepton decay channel), owing to its better description of the number of jets in the event.⁹

5.3.1 $\mathbf{p}_T^{\text{miss}}$ distributions in $Z \rightarrow \ell\ell$ events

Figures 5.12, 5.13, 5.14, and 5.15 on the following four pages show the Data to Monte Carlo simulation comparisons for the x , y , and transverse components, and scalar Σp_T , of the nominal (always top) and object-corrected (always bottom) $\mathbf{p}_T^{\text{miss}}$, in $Z \rightarrow \mu\mu$ (always left) and $Z \rightarrow ee$ (always right) events. The backgrounds shown are those described, ordered by their (weighted) integral so that all background distributions are visible. The bottom panel in each plot shows the ratio between the observed data and the total predicted background (which we expect to be close to 1). The error on the ratio points is calculated from the statistical uncertainty of the observed data, and the grey error bands show the total uncertainty from the expected background.

In general, we see a good agreement between the data and the simulated backgrounds for the x , y , and transverse components of both the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$, particularly in the peaks but with some discrepancy in the tails where statistics are low. The distributions are highly sensitive to track mismodelling, however, which can be seen most noticeably in the Σp_T distributions (figure 5.15) since the scalar sum of the track momenta is sensitive to both the number of tracks included and their $\mathbf{p}_T$. This is mitigated somewhat in the object-corrected $\mathbf{p}_T^{\text{miss}}$, however. A breakdown of the mismodelling is also given in appendix B.2, where the Data/Monte Carlo distributions for each of the terms used in the $\mathbf{p}_T^{\text{miss}}$ calculations are shown and discussed. We also expect some background contribution from QCD processes in these events, particularly in the low $\mathbf{E}_T^{\text{miss}}$ region. These processes are not well simulated (see section 3.4) and therefore are not included in the background set, giving rise to the discrepancy in the data/Monte Carlo ratio in this region.

⁹Again, see appendix B for the relevant n_{jets} plots.

5.3.2 $\mathbf{p}_T^{\text{miss}}$ distributions in $W \rightarrow \ell\nu$ events

Similarly, the $\mathbf{p}_T^{\text{miss}}$ and scalar Σp_T distributions are shown for $W \rightarrow \mu\nu$ and $W \rightarrow e\nu$ events in figures 5.16, and 5.17 respectively. Again we see the shift in the peak of the $\mathbf{p}_T^{\text{miss}}$ distribution owing to the presence of real $\mathbf{E}_T^{\text{miss}}$ in the event. The discrepancies in the Data/Background modeling in the low $\mathbf{p}_T^{\text{miss}}$ region are again due to the multijet background, processes that are not easily predictable using Monte Carlo only, and are hence not included in the simulation (see section 3.4). This QCD background mostly affects the low $\mathbf{p}_T^{\text{miss}}$ region, though some contribution can also be expected in the tail of the distributions, with more effect in the electron channel. Again, the Σp_T is most sensitive to the track mismodeling over all values (as well as to the QCD background for low values of Σp_T).

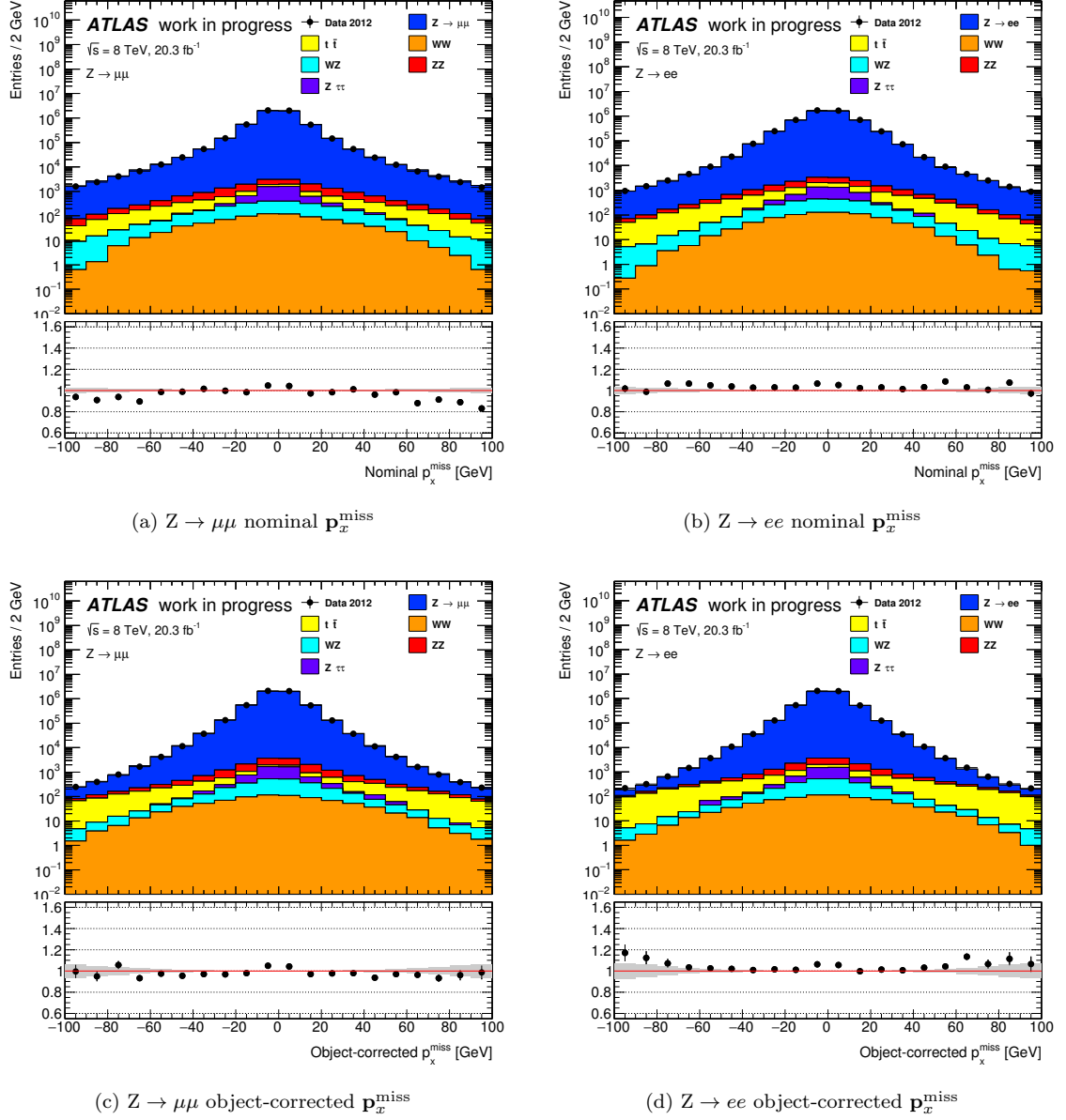


Figure 5.12: Data-to-Monte Carlo comparisons of the x component of the nominal (top) and object-corrected (bottom) $\mathbf{p}_T^{\text{miss}}$, in $Z \rightarrow \mu\mu$ (left) and $Z \rightarrow ee$ (right) events.

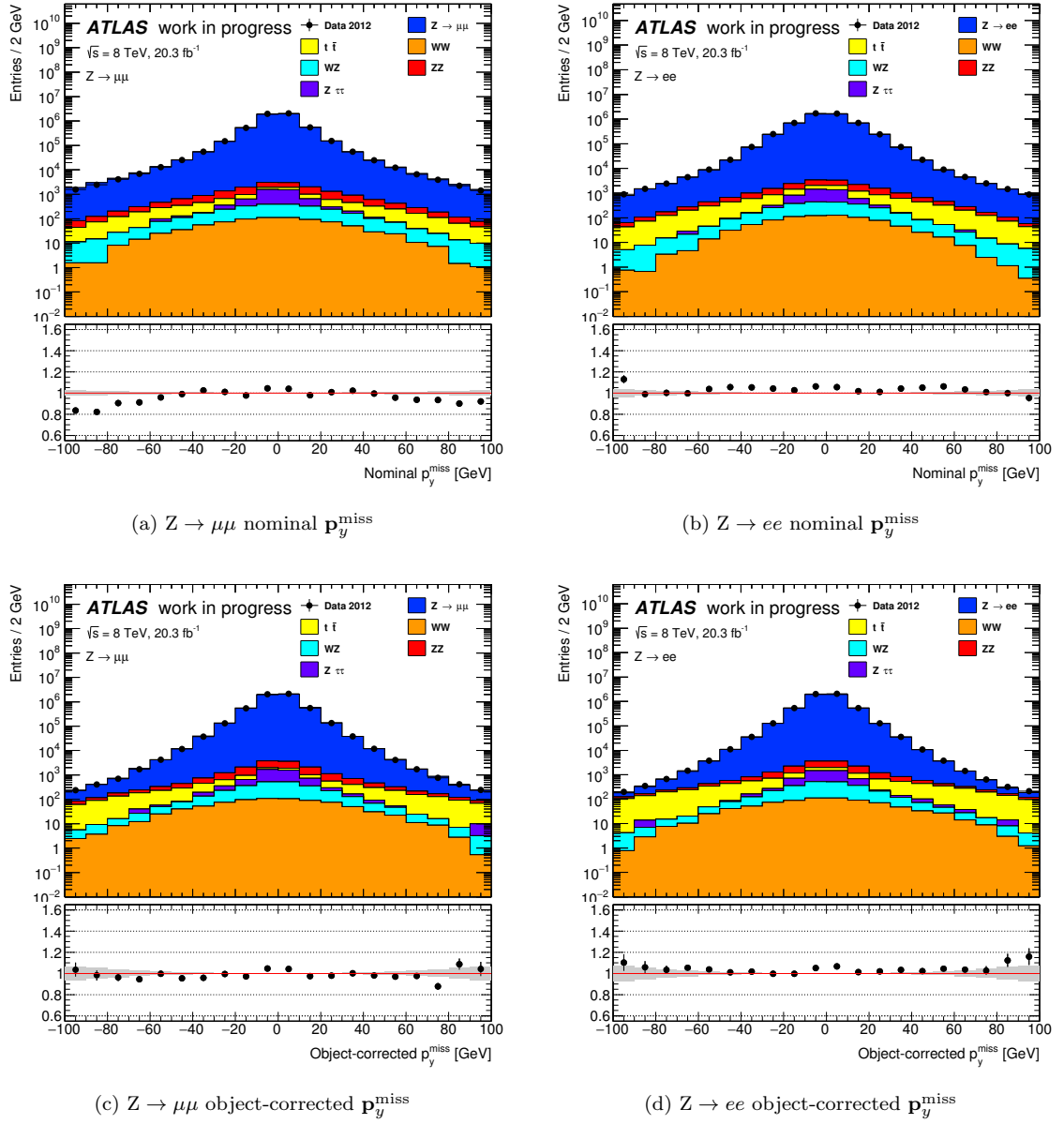


Figure 5.13: Data-to-Monte Carlo comparisons of the y component of the nominal (top) and object-corrected (bottom) $\mathbf{p}_T^{\text{miss}}$, in $Z \rightarrow \mu\mu$ (left) and $Z \rightarrow ee$ (right) events.

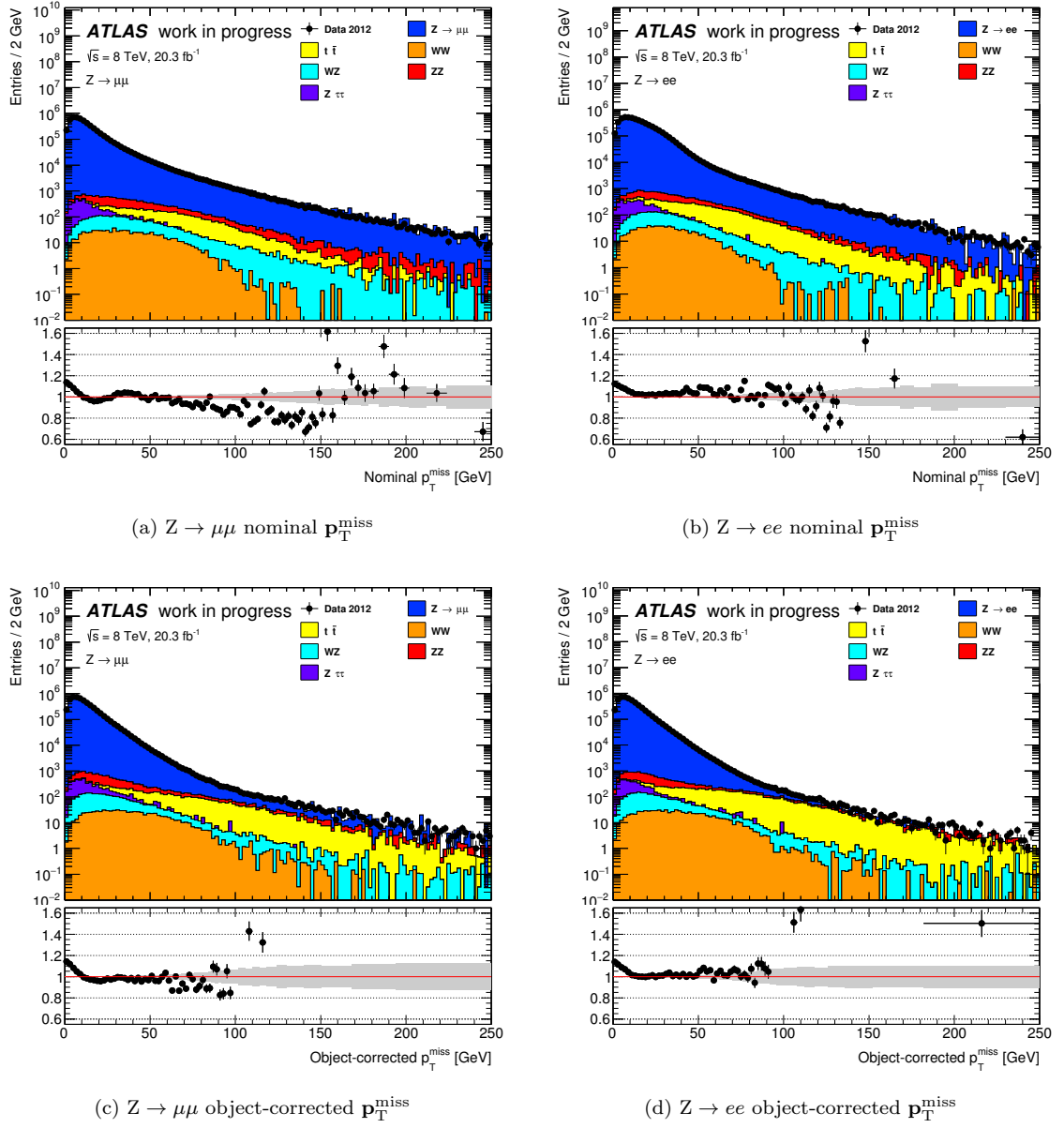


Figure 5.14: Data-to-Monte Carlo comparisons of the nominal (top) and object-corrected (bottom) $\mathbf{p}_T^{\text{miss}}$, in $Z \rightarrow \mu\mu$ (left) and $Z \rightarrow ee$ (right) events.

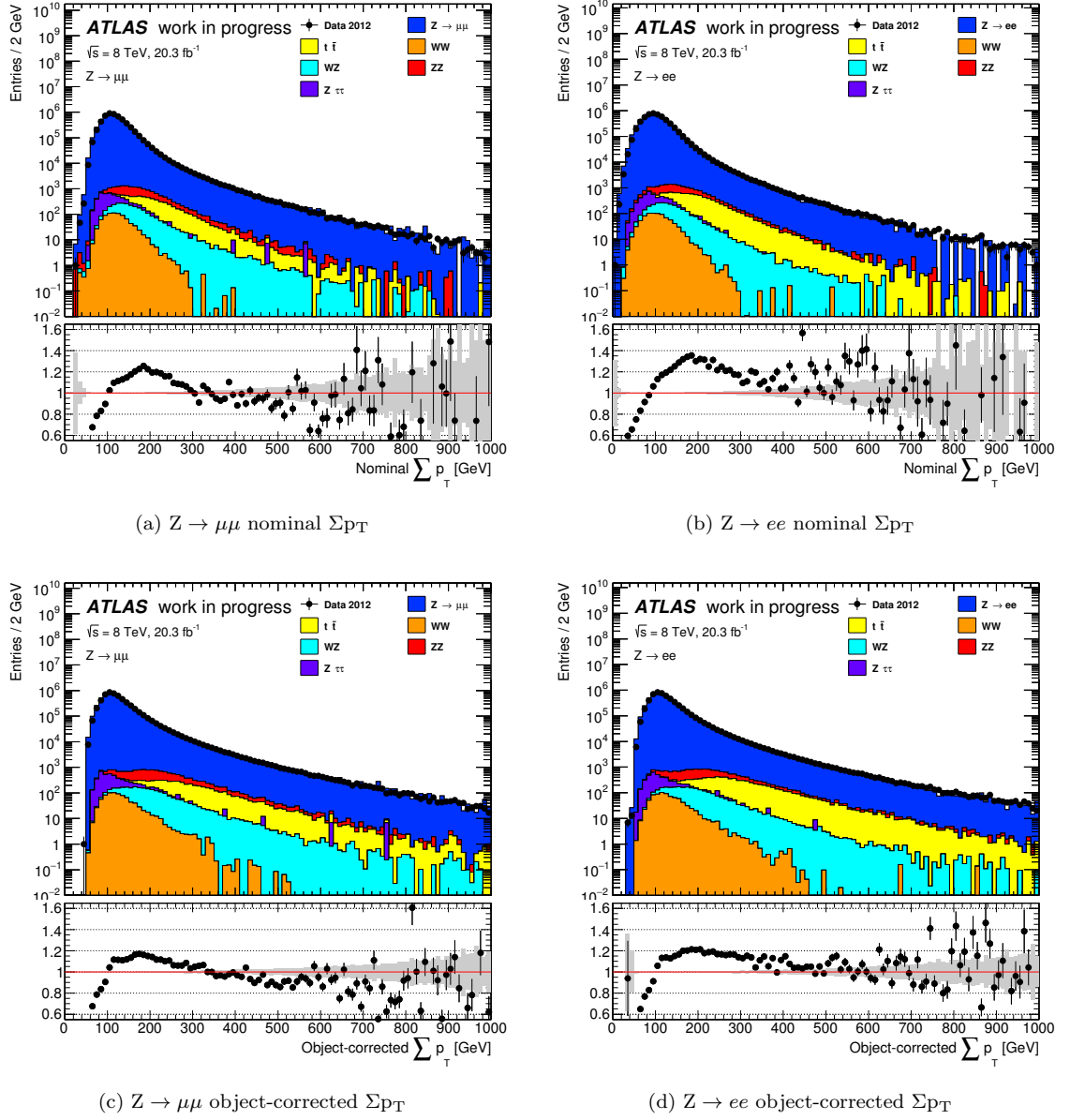


Figure 5.15: Data-to-Monte Carlo comparisons of the nominal (top) and object-corrected (bottom) scalar Σp_T distributions in $Z \rightarrow \mu\mu$ (left) and $Z \rightarrow ee$ (right) events.

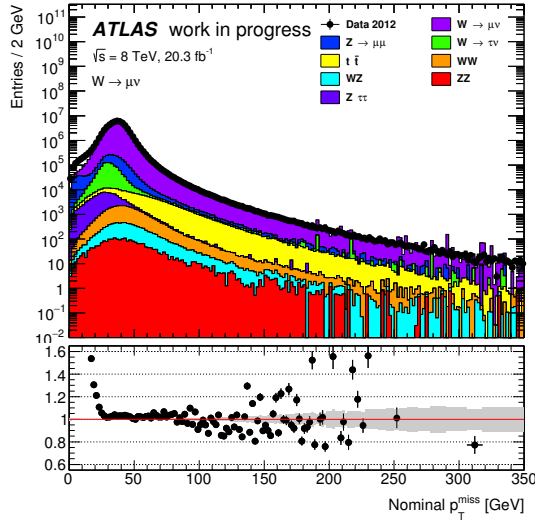
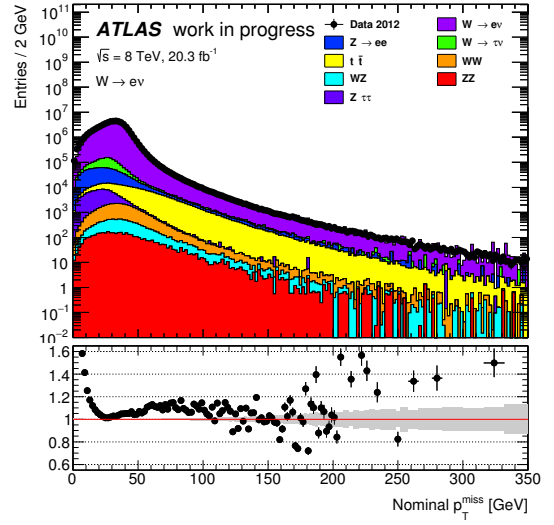
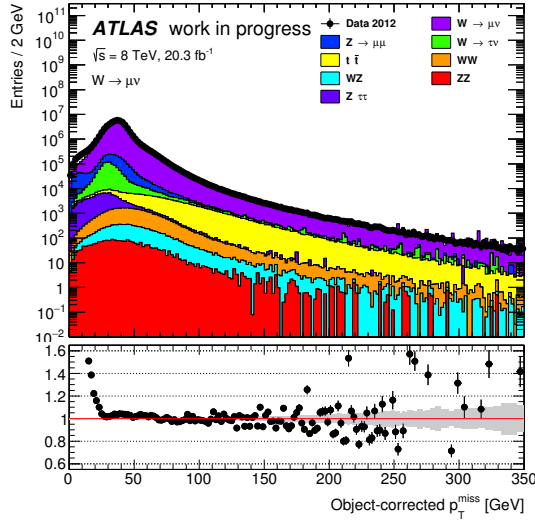
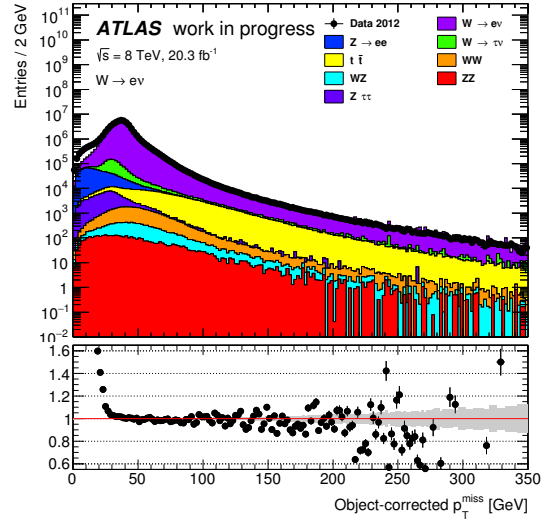
(a) $W \rightarrow \mu\nu$ nominal $\mathbf{p}_T^{\text{miss}}$ (b) $W \rightarrow e\nu$ nominal $\mathbf{p}_T^{\text{miss}}$ (c) $W \rightarrow \mu\nu$ object-corrected $\mathbf{p}_T^{\text{miss}}$ (d) $W \rightarrow e\nu$ object-corrected $\mathbf{p}_T^{\text{miss}}$

Figure 5.16: Data-to-Monte Carlo comparisons of the nominal (top) and object-corrected (bottom) $\mathbf{p}_T^{\text{miss}}$, in $W \rightarrow \mu\nu$ (left) and $W \rightarrow e\nu$ (right) events.

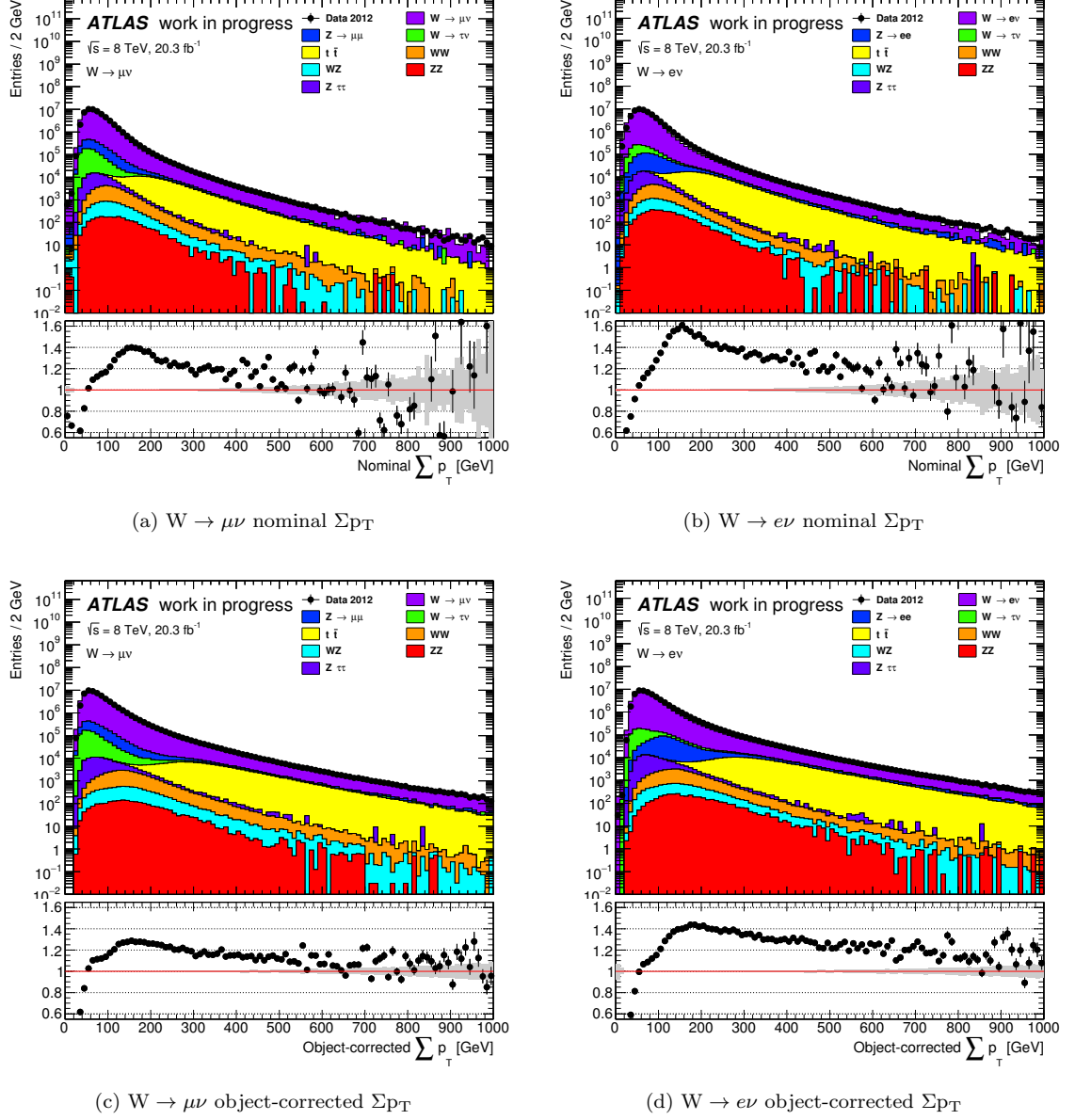


Figure 5.17: Data-to-Monte Carlo comparisons of the nominal (top) and object-corrected (bottom) scalar Σp_T distributions in $W \rightarrow \mu\nu$ (left) and $W \rightarrow e\nu$ (right) events.

5.4 $\mathbf{p}_T^{\text{miss}}$ Performance with respect to Event Activity

We have seen above that the $\mathbf{p}_T^{\text{miss}}$ algorithms do well to describe the activity in the hard scatter event. We now turn our attention to the stability of the algorithms as event-related quantities (such as pileup) change. As mentioned before, since the $\mathbf{p}_T^{\text{miss}}$ is a primary-vertex-based quantity it is expected to be particularly stable with respect to pileup, and to quantify its performance we can measure the resolution of the $\mathbf{p}_T^{\text{miss}}$ as a function of pileup-related variables.

There are three separate albeit correlated quantities we can use to measure the amount of pileup in a particular pp bunch crossing: the average number of interactions per crossing, denoted $\langle\mu\rangle$; the number of reconstructed primary vertices in the event, N_{pv} ; and the ΣE_T which also gives us a measure of event activity. To define the resolution, we plot the x and y components of the $\mathbf{p}_T^{\text{miss}}$ in bins of these variables. The resolution per bin is obtained by fitting a Gaussian to the x and y distributions to extract the width $\sigma_{x,y}$ of the peak; in W events the truth $\mathbf{E}_T^{\text{miss}}$ quantity is first subtracted from the $\mathbf{p}_T^{\text{miss}}$ to give a distribution centred around 0 before the fit takes place.

5.4.1 $\mathbf{p}_T^{\text{miss}}$ x and y Resolution

Figure 5.18 shows this resolution as a function of $\langle\mu\rangle$ for $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events, for the nominal (a) and object-corrected (b) $\mathbf{p}_T^{\text{miss}}$. The effect of the electron momentum loss due to Bremsstrahlung is clearly seen for the nominal case in the broader distribution and hence worse resolution; when this is taken into account for the object-corrected $\mathbf{p}_T^{\text{miss}}$ the electron and muon channel resolutions compare well. The plots show good agreement between data and simulation, but most noticeable, of course, is the excellent pileup stability, with an increase of less than 1 GeV over the full range of $\langle\mu\rangle$.

For a comparison with W boson events, we show the resolution in the electron channel - again for both the nominal and object-corrected versions of $\mathbf{p}_T^{\text{miss}}$ - as functions of N_{pv} and ΣE_T in figure 5.19 (a) and (b) respectively. The good agreement between the resolutions for the W and Z channels, as

well as the stability against N_{pv} and low increase versus ΣE_T indicate good performance all round for the $\mathbf{p}_T^{\text{miss}}$ algorithms.

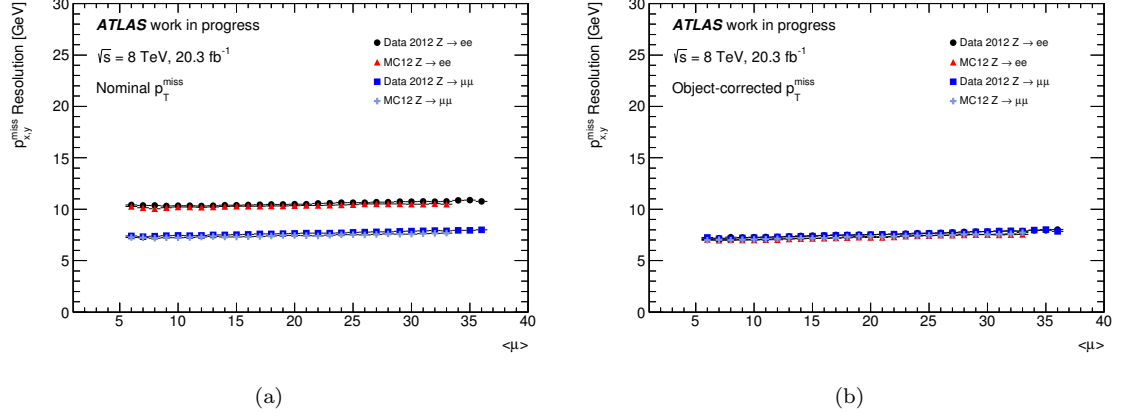


Figure 5.18: Resolution of the x and y components of the nominal (a) and object-corrected (b) $\mathbf{p}_T^{\text{miss}}$ for $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events, as a function of the average number of interactions per bunch crossing $\langle\mu\rangle$.

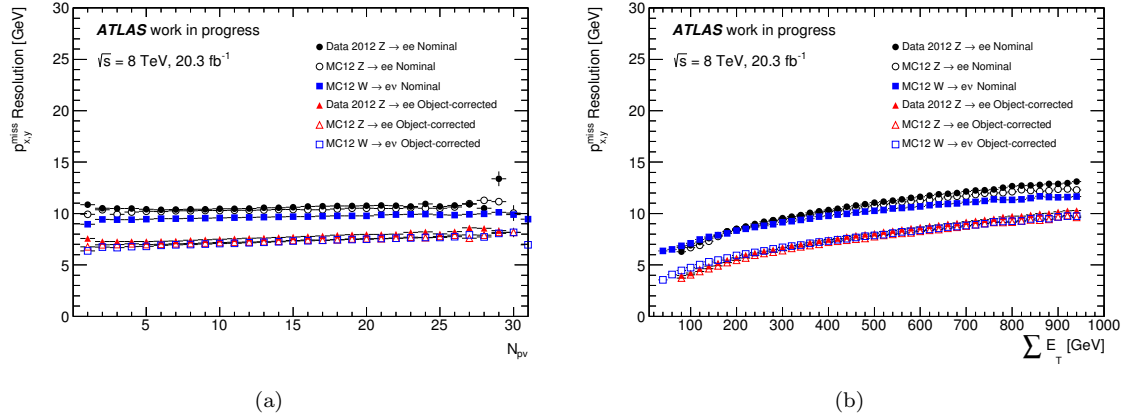


Figure 5.19: Resolution of the x and y components of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ for $Z \rightarrow ee$ and $W \rightarrow ev$ events as a function of the number of reconstructed vertices in the event (a) and the scalar sum of the total transverse energy in the calorimeter (b).

A summary of the values of the resolutions of figure 5.19 (a) (as well as the muon channel) is given in table 5.3. For the resolution as a function of ΣE_T , we can parameterise the distribution with respect to $\sqrt{\Sigma E_T}$ as:

$$y = k\sqrt{\Sigma E_T} + c \quad (5.2)$$

where k and c are constants obtained from a fit of the above function to the resolution. The k -values are also shown in the table below (c is ideally 0 and, in these fits, effectively 0, and so is not shown).

Table 5.3: $\mathbf{p}_T^{\text{miss}}$ resolution and ΣE_T fit values

	$Z \rightarrow ee$ Data	$Z \rightarrow ee$ MC	$W \rightarrow e\nu$ MC
Nominal $\mathbf{p}_T^{\text{miss}}$ resolution vs N_{pv} [GeV]	10.49	10.33	9.63
Object-corrected $\mathbf{p}_T^{\text{miss}}$ resolution vs N_{pv} [GeV]	7.54	7.23	7.15
Nominal $\mathbf{p}_T^{\text{miss}}$ fit to ΣE_T (k)	0.28	0.26	0.21
Object-corrected $\mathbf{p}_T^{\text{miss}}$ fit to ΣE_T (k)	0.28	0.26	0.24
	$Z \rightarrow \mu\mu$ Data	$Z \rightarrow \mu\mu$ MC	$W \rightarrow \mu\nu$ MC
Nominal $\mathbf{p}_T^{\text{miss}}$ resolution vs N_{pv} [GeV]	7.63	7.40	7.12
Object-corrected $\mathbf{p}_T^{\text{miss}}$ resolution vs N_{pv} [GeV]	7.51	7.28	7.02
Nominal $\mathbf{p}_T^{\text{miss}}$ fit to ΣE_T (k)	0.27	0.26	0.20
Object-corrected $\mathbf{p}_T^{\text{miss}}$ fit to ΣE_T (k)	0.29	0.28	0.22

5.4.2 Directional Resolution

For the events with real $\mathbf{E}_T^{\text{miss}}$ the effect on the direction with added pileup is also important; here one can use the width of the $\Delta\phi$ distribution, again fitted with a gaussian, as a measure of the directional stability. Figure 5.20 (a) shows the function of the $\Delta\phi$ width between the $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ for increasing N_{pv} , for both the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$. One can see that the distribution is pileup dependent - this is purely a result of the pileup dependence of the calorimetric $\mathbf{E}_T^{\text{miss}}$, as can be seen in figure 5.20 (b), where the $\Delta\phi$ width between the $\mathbf{E}_T^{\text{miss}}$, nominal or object-corrected $\mathbf{p}_T^{\text{miss}}$ and the true $\mathbf{E}_T^{\text{miss}}$ are shown. Here, the pileup dependence of both $\mathbf{p}_T^{\text{miss}}$ versions with respect to the truth is clear, and it is only the width of the $\mathbf{E}_T^{\text{miss}}$ distribution that increases with N_{pv} , making the $\Delta\phi$ cut a useful quantity not only for rejecting backgrounds that fake $\mathbf{E}_T^{\text{miss}}$, but also events with fake $\mathbf{E}_T^{\text{miss}}$ from pileup. A consequence of the pileup dependence for physics analyses using a very tight $\Delta\phi(\mathbf{E}_T^{\text{miss}}, \mathbf{p}_T^{\text{miss}})$ cut, however, is that the value of the cut may need to be adjusted for events with more pileup events.

5.5 $\mathbf{p}_T^{\text{miss}}$ Response

Possibly the most crucial component of any $\mathbf{E}_T^{\text{miss}}$ -related measurement is its response (or alternatively, how well the particular algorithm measures the scale of the event), since the magnitude

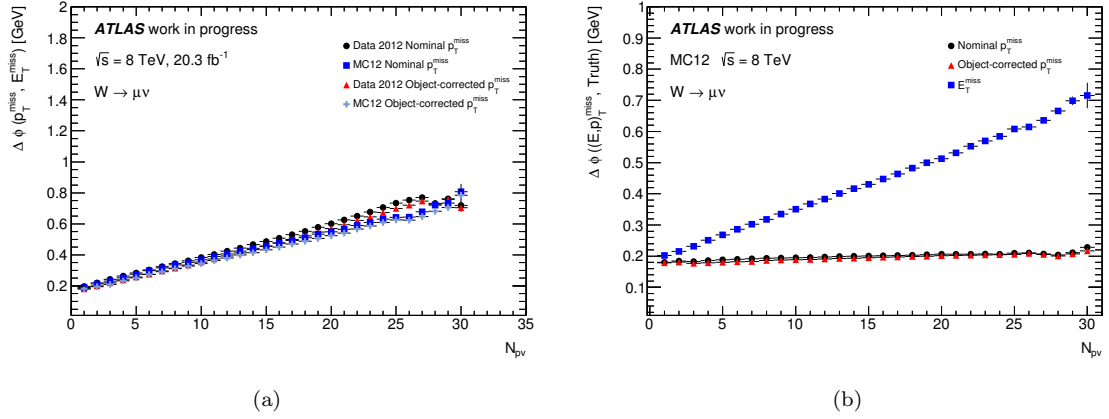


Figure 5.20: $\Delta\phi$ width between the $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ (a) and between the $\mathbf{p}_T^{\text{miss}}$ or $\mathbf{E}_T^{\text{miss}}$ and the true $\mathbf{E}_T^{\text{miss}}$ (b) as a function of the number of reconstructed vertices in $W \rightarrow \mu\nu$ events.

of the $\mathbf{E}_T^{\text{miss}}$ is among one of the most regularly used variables in analyses with real $\mathbf{E}_T^{\text{miss}}$. The performance of the algorithm depends on the magnitude of the $\mathbf{E}_T^{\text{miss}}$, with its various advantages and disadvantages dictating somewhat the scales at which the algorithm is the most efficient. For example, in events where the $\mathbf{E}_T^{\text{miss}}$ is expected to be extremely large, such as in SUSY searches, the contributions from QCD processes in pileup vertices play a comparatively small role overall for the magnitude of the $\mathbf{E}_T^{\text{miss}}$; an advantage for the calorimeter-based measurement, albeit one that is a disadvantage when events with low values of $\mathbf{E}_T^{\text{miss}}$ are considered. The Z and W boson events are therefore well suited to cover the region from low to high values of $\mathbf{E}_T^{\text{miss}}$, providing a good overall perspective of the response of the $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ algorithms.

The response can be checked in various ways which differ depending on the presence of real $\mathbf{E}_T^{\text{miss}}$ in the event. In $Z \rightarrow \ell\ell$ events we use the projection along the transverse direction of the Z boson to measure the balance between all the components that comprise the $\mathbf{E}_T^{\text{miss}}$ or $\mathbf{p}_T^{\text{miss}}$. In $W \rightarrow \ell\nu$ events, we can use the truth $\mathbf{E}_T^{\text{miss}}$ quantity as our metric, studying the magnitude and linearity of the reconstructed quantity. And finally, the response can be inferred by considering the reconstructed mass in $W \rightarrow \ell\nu$ events where part of the mass comes from the unobserved neutrino.

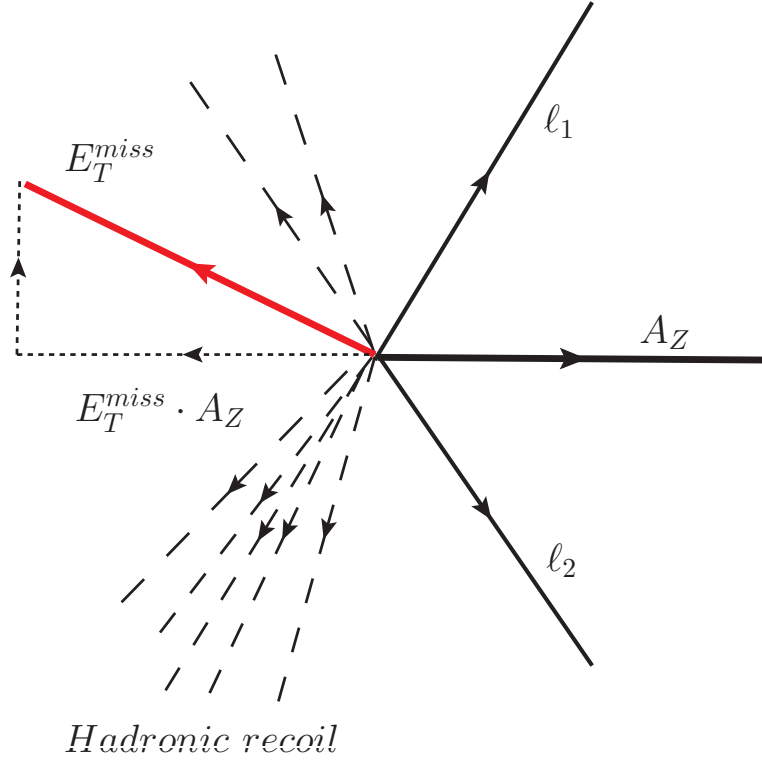


Figure 5.21: Schematic diagram of the projection $\mathbf{E}_T^{\text{miss}} \cdot \mathbf{A}_Z$ of the $\mathbf{E}_T^{\text{miss}}$ along the direction of the Z boson, which is sensitive to the balance between the hard leptons and the hadronic recoil in the reconstruction.

5.5.1 Final states with no real $\mathbf{E}_T^{\text{miss}}$ (scale in $Z \rightarrow \ell\ell$ events)

In $Z \rightarrow \ell\ell$ events, one can define the axis of reconstructed transverse momentum of the Z boson, $\mathbf{A}_Z$, using the transverse momenta of the two selected leptons ($\mathbf{p}_T^{\ell_{1,2}}$) from the Z decay:

$$\mathbf{A}_Z = \frac{\mathbf{p}_T^{\ell_1} + \mathbf{p}_T^{\ell_2}}{|\mathbf{p}_T^{\ell_1} + \mathbf{p}_T^{\ell_2}|} \quad (5.3)$$

This vector acts as an axis along which the $\mathbf{E}_T^{\text{miss}}$ measurement becomes sensitive to detector resolution and biases [61]. The projection of the $\mathbf{E}_T^{\text{miss}}$ along this axis therefore provides us with a useful diagnostic metric sensitive to the balance between the hard leptons and the hadronic recoil.

A schematic diagram of the $Z \rightarrow \ell\ell$ event topology defining this diagnostic is shown in figure 5.21. The vector $\mathbf{A}_Z$ is defined by the two leptons from the Z boson decay; also shown is extra hadronic

activity from the underlying event. The reconstructed $\mathbf{E}_T^{\text{miss}}$ is indicated by the red line, with the projection $\mathbf{E}_T^{\text{miss}} \cdot \mathbf{A}_Z$ indicated by the dashed line antiparallel to $\mathbf{A}_Z$.

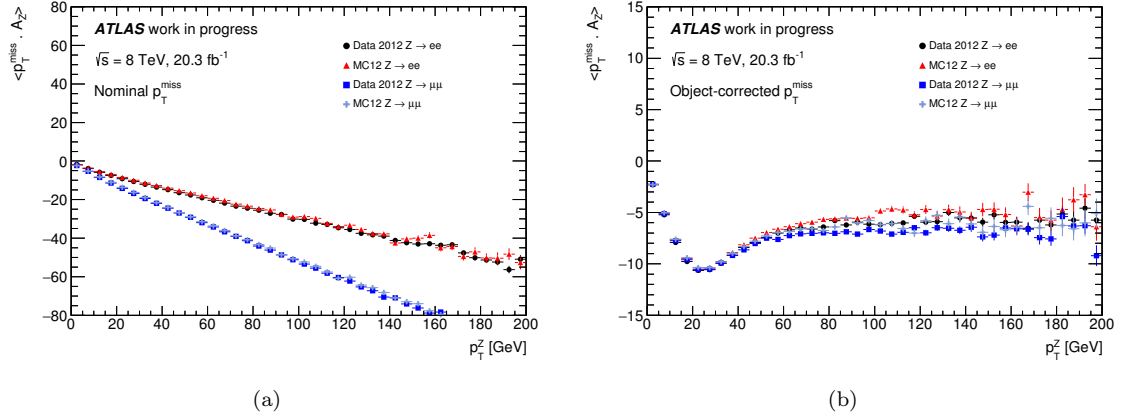


Figure 5.22: Diagnostic plot showing the mean value of the projection $\mathbf{E}_T^{\text{miss}} \cdot \mathbf{A}_Z$ as a function of the reconstructed transverse momentum of the Z boson, for the nominal (a) and object-corrected (b) $\mathbf{p}_T^{\text{miss}}$ in $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events.

Ideally, if the full event's momentum contributions were to be taken into account, with no loss from detector or reconstruction efficiencies, the mean value of the projection $\langle \mathbf{E}_T^{\text{miss}} \cdot \mathbf{A}_Z \rangle$ should be centred around zero for all values of the Z boson $\mathbf{p}_T$ ($\mathbf{p}_T^Z$). However, for the nominal $\mathbf{p}_T^{\text{miss}}$, we have already seen that we lose out on a significant fraction of the event transverse momentum when jets are present in the event (through the missed neutral particles). Therefore, as the $\mathbf{p}_T^Z$ and the contribution from neutral particles in jets increases, we expect $\langle \mathbf{p}_T^{\text{miss}} \cdot \mathbf{A}_Z \rangle$ to increase accordingly. This is shown clearly in figure 5.22 (a) for both the muon and electron channels with good agreement between data and simulation, where the negative bias suggests that the underlying hadronic activity is underestimated by the $\mathbf{p}_T^{\text{miss}}$ soft track term. An additional feature that can be seen is the difference in the slope between the two channels; this is another effect of the momentum loss due to electron Bremsstrahlung which affects the nominal $\mathbf{p}_T^{\text{miss}}$.

Consequently, the object-corrected $\mathbf{p}_T^{\text{miss}}$ should then show the expected flat distribution if the inclusion of the full jet and electron $\mathbf{p}_T$ recovers most of the lost momentum in the event. The corresponding $\langle \mathbf{p}_T^{\text{miss}} \cdot \mathbf{A}_Z \rangle$ distributions for the object-corrected $\mathbf{p}_T^{\text{miss}}$ are shown in figure 5.22 (b), and such a levelling-off of the distribution is indeed visible at around ~ 6 GeV. Again the negative bias is seen indicating that the hadronic event activity is still underestimated, most likely owing to neutral particles from jets with $\mathbf{p}_T$ below the threshold for our selections. The bias is enhanced in

particular in the region of $\mathbf{p}_T^Z$ below ~ 40 GeV where events without (hard) jets dominate, since the relative fraction of these contributions to the soft term is larger in this region.

We can use the ratio of the projection $\mathbf{p}_T^{\text{miss}} \cdot \mathbf{A}_Z$ and $\mathbf{p}_T^Z$ to measure the balance between the hard and underlying event terms in the $\mathbf{p}_T^{\text{miss}}$. By defining the diagnostic scale as:

$$\text{Scale} = \langle 1 - \left| \frac{\mathbf{p}_T^{\text{miss}} \cdot \mathbf{A}_Z}{\mathbf{p}_T^Z} \right| \rangle \quad (5.4)$$

(where the limit is 0 when none of the hadronic recoil to balance the Z is reconstructed, and 1 when the full $\mathbf{p}_T$ of the jet is taken into account) we can quantify the contribution to the underestimation of the hadronic recoil, from both the soft term and neutral particles in hard jets.

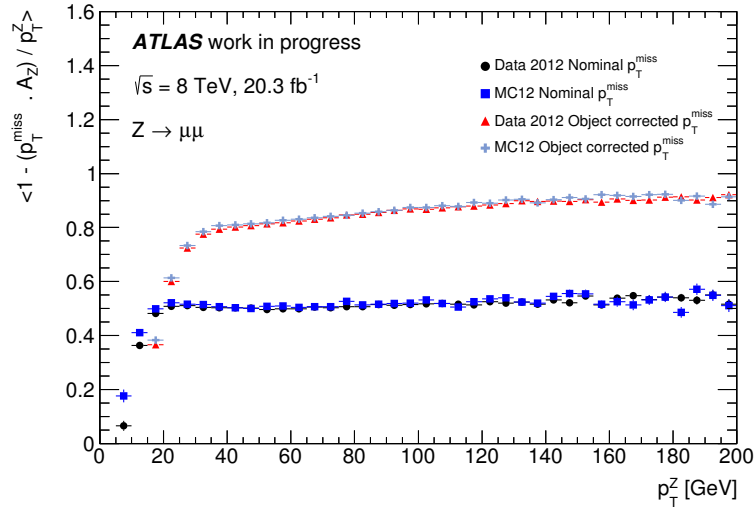


Figure 5.23: Diagnostic scale showing the average percentage of the hadronic event activity reconstructed by the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ as a function of the transverse momentum of the Z boson in $Z \rightarrow \mu\mu$ events with 1 central jet.

The most effective use of this measurement is in events where the full event activity falls within the inner detector acceptance, so again we use the pseudorapidity requirements defined above to select $Z + 1$ jet events (ie $|\eta_{Z,jet}| < 2.0$). By considering the scale for both the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$, we are thus able to infer the influence on the $\mathbf{p}_T^{\text{miss}}$ response from the combined effect of neutral particles in jets, out-of-acceptance particles, and of detector and reconstruction inefficiencies. Figure 5.23 shows this scale in $Z \rightarrow \mu\mu$ events for both data and MC simulation, and the difference in scale between the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ is clear. Apart from the “turn-on” between 20 and 30 GeV for the nominal and object-corrected versions respectively, the

curves are mostly flat for the remainder of the range of $\mathbf{p}_T^Z$. This turn-on region corresponds to that of the enhanced negative bias in figure 5.22 for the same reason: the underestimation in the soft term plays a greater role here, but is minimised once harder objects come into account.

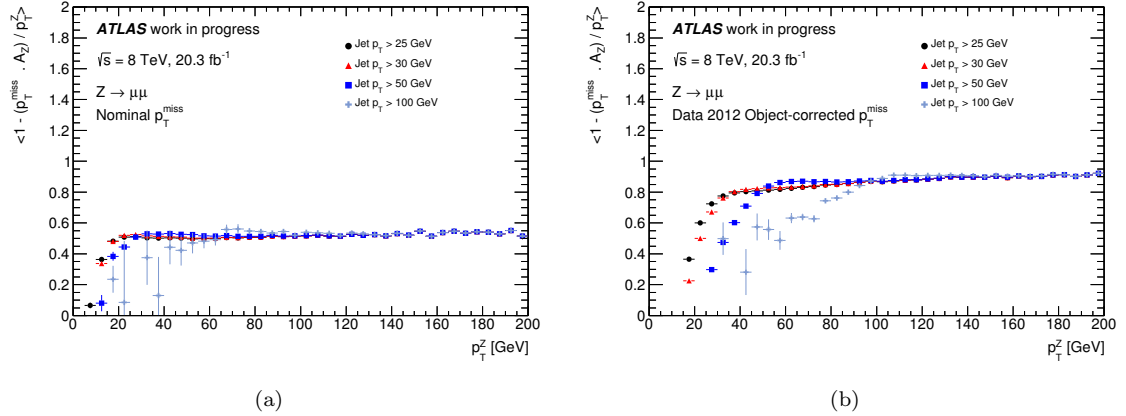


Figure 5.24: Diagnostic scale showing the average percentage of the hadronic event activity reconstructed by the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ as a function of the transverse momentum of the Z boson in $Z \rightarrow \mu\mu$ events with 1 central jet, for various values of the jet transverse momentum.

The scale of the object-corrected $\mathbf{p}_T^{\text{miss}}$ shows that when the full object $\mathbf{p}_T$ is used we are able to account for between 80 and 90% of the scale of the event. This is a near-complete reconstruction, with the last 10% underestimation due to missed particles from acceptance limitations or detector and reconstruction inefficiencies. The nominal $\mathbf{p}_T^{\text{miss}}$ scale shows only a 50% complete reconstruction which, taking the acceptance and inefficiencies into account, aligns well with our expectations that the nominal $\mathbf{p}_T^{\text{miss}}$ recovers the charged component of the jet. And again, the data is well described by the simulation. As a final check, figure 5.24 shows that the scale is independent of the $\mathbf{p}_T$ of the jet in the event, with only the turn-on point shifting accordingly as the jet $\mathbf{p}_T$ is increased.

5.5.2 Final states with real $\mathbf{E}_T^{\text{miss}}$ (linearity of $W \rightarrow \ell\nu$ events)

In the $W \rightarrow \ell\nu$ events we have real $\mathbf{E}_T^{\text{miss}}$ against which to compare the scale of our $\mathbf{p}_T^{\text{miss}}$, and in particular we can use the truth $\mathbf{E}_T^{\text{miss}}$ quantity from Monte Carlo simulation samples for testing against the ideal case. Figure 5.25 (a) shows the mean value of the nominal and object-corrected versions of $\mathbf{p}_T^{\text{miss}}$ as a function of the true $\mathbf{E}_T^{\text{miss}}$ for $W \rightarrow \mu\nu$ events. We can see the offset of the nominal $\mathbf{p}_T^{\text{miss}}$ with respect to the true $\mathbf{E}_T^{\text{miss}}$ as the true $\mathbf{E}_T^{\text{miss}}$ increases (and hence, the number

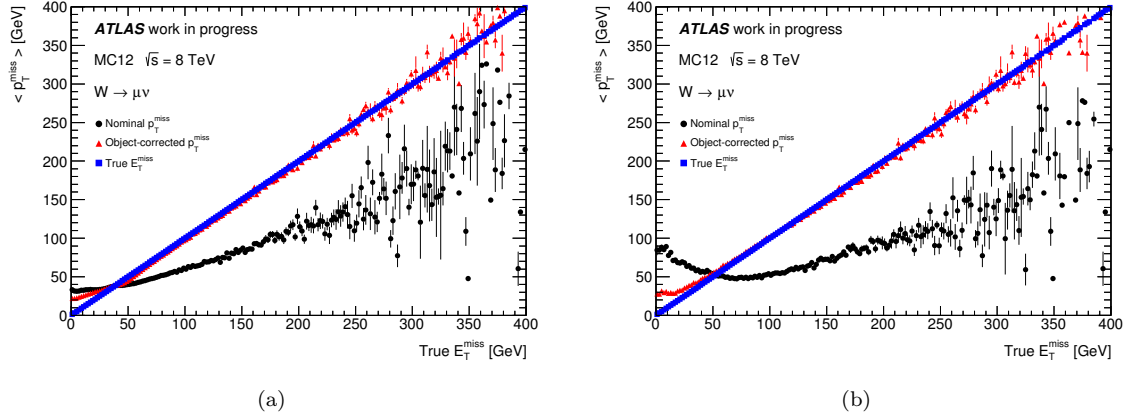


Figure 5.25: Mean value of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ as a function of true $\mathbf{E}_T^{\text{miss}}$ in $W \rightarrow \mu\nu$ events, for the inclusive case (a) and events where $\mathbf{p}_T^W > 120$ GeV (b).

of jets increases, as the neutrino picks up the boost from the W), though in the region around true $\mathbf{E}_T^{\text{miss}} \sim 40$ GeV the nominal $\mathbf{p}_T^{\text{miss}}$ recovers the true $\mathbf{E}_T^{\text{miss}}$ almost exactly. In comparison, the object-corrected $\mathbf{p}_T^{\text{miss}}$ matches the true $\mathbf{E}_T^{\text{miss}}$ almost completely.

To extend the measurements to higher $\mathbf{p}_T$ scales, we consider in figure 5.25 (b) the same plot for the boosted W regime, where the $\mathbf{p}_T$ of the W boson is required to be above 120 GeV. The offset of the nominal $\mathbf{p}_T^{\text{miss}}$ from the truth is more pronounced here, as expected with a larger $\mathbf{p}_T$ contribution from jets in this kinematic region, while the object-corrected $\mathbf{p}_T^{\text{miss}}$ still shows excellent agreement.

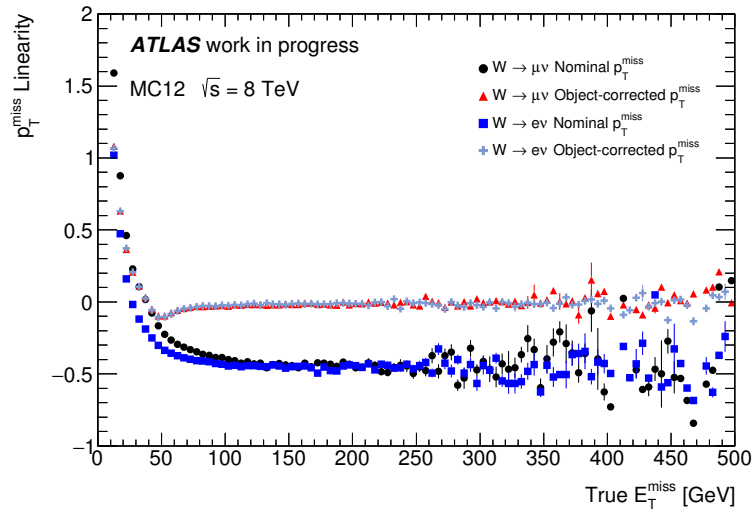


Figure 5.26: Nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ linearity with respect to the true $\mathbf{E}_T^{\text{miss}}$ in $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ events.

The linearity of the $\mathbf{p}_T^{\text{miss}}$ with respect to the true $\mathbf{E}_T^{\text{miss}}$ is defined as the ratio:

$$\text{Linearity} = \left\langle \frac{p_T^{\text{miss}} - E_T^{\text{miss,truth}}}{E_T^{\text{miss,truth}}} \right\rangle \quad (5.5)$$

which gives an expected value of zero if the $\mathbf{p}_T^{\text{miss}}$ is reconstructed at the correct scale. The linearity distributions for the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ is shown in figure 5.26 for both $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ events. A positive bias is visible in the region of very low true $\mathbf{E}_T^{\text{miss}}$, owing to the finite resolution of the $\mathbf{p}_T^{\text{miss}}$ and the domination of contributions in the soft track term. At larger values of true $\mathbf{E}_T^{\text{miss}}$, the bias is within 5% for the object-corrected $\mathbf{p}_T^{\text{miss}}$, with a larger negative bias in the nominal $\mathbf{p}_T^{\text{miss}}$ as expected. Differences in the linearity for the electron and muon channels can also be seen for the nominal $\mathbf{p}_T^{\text{miss}}$, where the electron momentum loss shows again in a worsening of the bias (though the effect at higher values of true $\mathbf{E}_T^{\text{miss}}$ is diminished).

5.5.3 Reconstruction of mass in final states with $\mathbf{E}_T^{\text{miss}}$ ($W \rightarrow \ell\nu$)

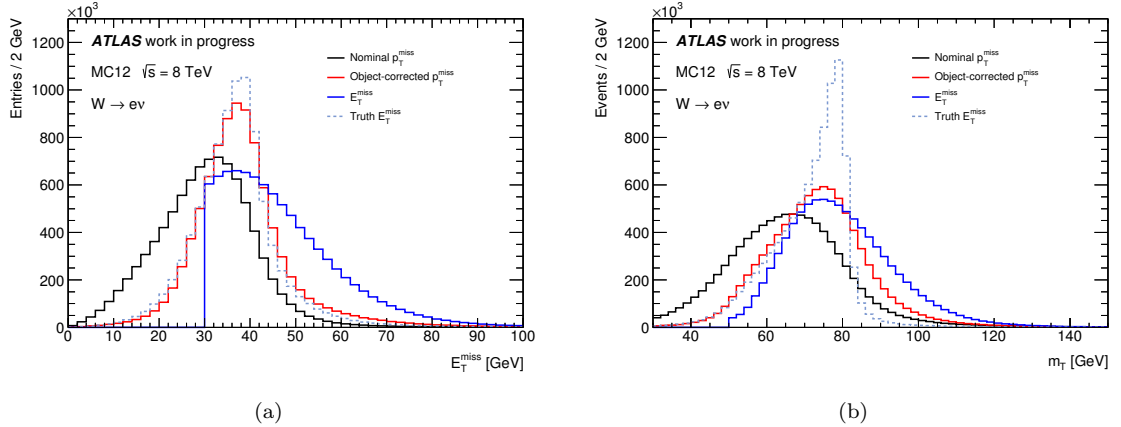


Figure 5.27: Comparison of the $\mathbf{E}_T^{\text{miss}}$, nominal $\mathbf{p}_T^{\text{miss}}$, and object-corrected $\mathbf{p}_T^{\text{miss}}$ distributions in $W \rightarrow e\nu$ events (a); and the transverse mass of the W boson calculated using the magnitude and direction of each $\mathbf{E}_T^{\text{miss}}$ -related quantity (b). Also shown for comparison are the relevant distributions using the true $\mathbf{E}_T^{\text{miss}}$.

Finally, the transverse mass of the W boson, m_T , reconstructed from the $\mathbf{p}_T$ of the selected lepton and the $\mathbf{E}_T^{\text{miss}}$ (as defined in equation 5.1) is a quantity that is sensitive to both the resolution and scale of the $\mathbf{E}_T^{\text{miss}}$. The magnitude and direction of the $\mathbf{E}_T^{\text{miss}}$ in equation 5.1 can be replaced by those of the $\mathbf{p}_T^{\text{miss}}$ to obtain a m_T reconstruction with our $\mathbf{p}_T^{\text{miss}}$ version of interest. Additionally,

we can use the truth $\mathbf{E}_T^{\text{miss}}$ in the equation for a comparison with the ideal case, while keeping the reconstructed lepton constant between the calculations.

Figure 5.27 (a) shows the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ distributions, and the $\mathbf{E}_T^{\text{miss}}$ distribution, in $W \rightarrow e\nu$ inclusive events. The hard cut on the $\mathbf{E}_T^{\text{miss}}$ distribution is due to the cut used for the event selections. Also shown is the true $\mathbf{E}_T^{\text{miss}}$, and we can see that the $\mathbf{p}_T^{\text{miss}}$ is closer to the true $\mathbf{E}_T^{\text{miss}}$ after the object correction. In figure 5.27 (b) the m_T distributions are shown, using the various $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ versions from (a) in the calculation, and again the improvement from the object-correction is evident.

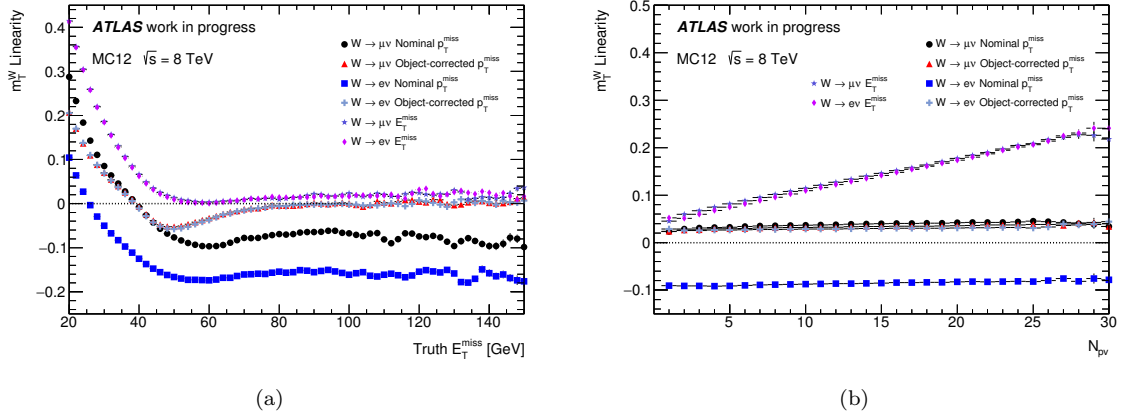


Figure 5.28: Linearity of the W mass calculated using the nominal $\mathbf{p}_T^{\text{miss}}$, object-corrected $\mathbf{p}_T^{\text{miss}}$, or $\mathbf{E}_T^{\text{miss}}$ and the selected lepton, with respect to the true $\mathbf{E}_T^{\text{miss}}$ (a) and the number of reconstructed vertices (b) in $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ events.

The linearity of the W transverse mass can be calculated using a similar formula to that of equation 5.5, this time using the true m_T , m_T^{truth} , as reference:

$$\text{Linearity} = \left\langle \frac{m_T - m_T^{\text{truth}}}{m_T^{\text{truth}}} \right\rangle \quad (5.6)$$

The linearity of the m_T reconstructed using the $\mathbf{E}_T^{\text{miss}}$, nominal $\mathbf{p}_T^{\text{miss}}$ and object-corrected $\mathbf{p}_T^{\text{miss}}$ can be seen in figure 5.28 for $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ events, as a function of the true $\mathbf{E}_T^{\text{miss}}$ (a), and the number of reconstructed vertices in the event (b). In figure 5.28 (a) the difference between the nominal $\mathbf{p}_T^{\text{miss}}$ in the electron and muon channels is again noticeable, and the improvement in the linearity for the object-corrected $\mathbf{p}_T^{\text{miss}}$ is evident. The m_T linearity calculated using the $\mathbf{E}_T^{\text{miss}}$ levels off near zero with only a small bias at the lowest value of the true $\mathbf{E}_T^{\text{miss}}$, providing a good

overall measurement especially in the high $\mathbf{E}_T^{\text{miss}}$ range. However, around values of true $\mathbf{E}_T^{\text{miss}} \sim 40$ GeV where the majority of these events fall, the scale as measured by the object-corrected (and nominal, in the muon channel) $\mathbf{p}_T^{\text{miss}}$ seems to provide the best measurement. Another interesting aspect to note is the dependency of the mass linearity with pileup (see figure 5.28 (b)). As expected, the mass linearity is independent of the number of reconstructed vertices for the $\mathbf{p}_T^{\text{miss}}$, but a pileup dependence is evident for the $\mathbf{E}_T^{\text{miss}}$ case. The estimation of the reconstructed m_T in W events may therefore be improved with the use of the $\mathbf{p}_T^{\text{miss}}$ in the m_T calculation.

5.6 $\mathbf{p}_T^{\text{miss}}$ Systematics

The largest contribution to the systematic uncertainty of the $\mathbf{p}_T^{\text{miss}}$ comes from the soft track term $\mathbf{p}_T^{\text{miss,soft}}$, since the hard part consists of leptons and jets with well-measured track $\mathbf{p}_T$ in the nominal case, or, in the object-corrected case, combined lepton $\mathbf{p}_T$ measurements with small systematic uncertainties and jets with a well-defined energy scale and resolution.

To evaluate the uncertainty on the soft term we consider the balance between it and the hard component of the $\mathbf{p}_T^{\text{miss}}$ in $Z \rightarrow \mu\mu$ events. The hard component, $\mathbf{p}_T^{\text{hard, trk}}$, can be defined as

$$\mathbf{p}_{x,y}^{\text{hard, trk}} = \sum_e \mathbf{p}_{x,y}^e + \sum_\mu \mathbf{p}_{x,y}^\mu + \sum_{jets} \mathbf{p}_{x,y}^{jets} + \sum_\nu \mathbf{p}_{x,y}^\nu \quad (5.7)$$

where $\sum_\nu \mathbf{p}_{x,y}^\nu \approx 0$ for $Z \rightarrow \mu\mu$ events. The $\mathbf{p}_T^{\text{miss,soft}}$ is then decomposed into components longitudinal and perpendicular to the $\mathbf{p}_T^{\text{hard, trk}}$ direction, given by $\mathbf{p}_T^{\text{miss,soft}_L}$ and $\mathbf{p}_T^{\text{miss,soft}_\perp}$ respectively (in a method equivalent to that used for the diagnostic plot in section 5.5) and give a measure of the scale that is measured by the soft term. The mean and resolution of the $\mathbf{p}_T^{\text{miss,soft}_L}$ and $\mathbf{p}_T^{\text{miss,soft}_\perp}$ are extracted from a Gaussian fit to the distributions, parametrised in bins of $\mathbf{p}_T^{\text{hard, trk}}$, jet multiplicity and $\langle\mu\rangle$, which take into account dependence on event topology and pileup. Six systematic variations are then performed: shifting the $\langle\mathbf{p}_T^{\text{miss,soft}_L}\rangle$ up and down, or scaling the $\mathbf{p}_T^{\text{miss,soft}_L}$ and $\mathbf{p}_T^{\text{miss,soft}_\perp}$ resolutions up or down in either a correlated (up-up or down-down) or anti-correlated (up-down or down-up) manner. The resulting distributions for the $\mathbf{p}_T^{\text{miss,soft}}$ are shown in figure 5.29 for both the inclusive and 0 jet cases, as well as for the full $\mathbf{p}_T^{\text{miss}}$ distributions in figure 5.30, and generally there is good closure between data and Monte Carlo, especially in the inclusive cases.

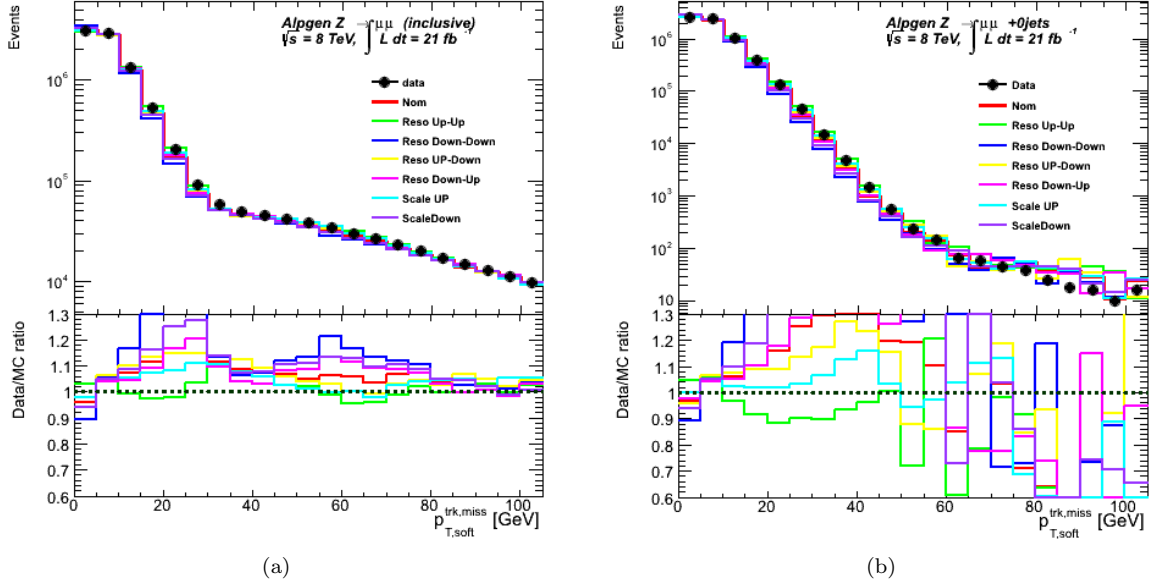


Figure 5.29: $\mathbf{p}_T^{\text{miss}}$ soft term systematic variations for $Z \rightarrow \mu\mu$ inclusive (a) and 0 jet (b) events. [F. Hariri]

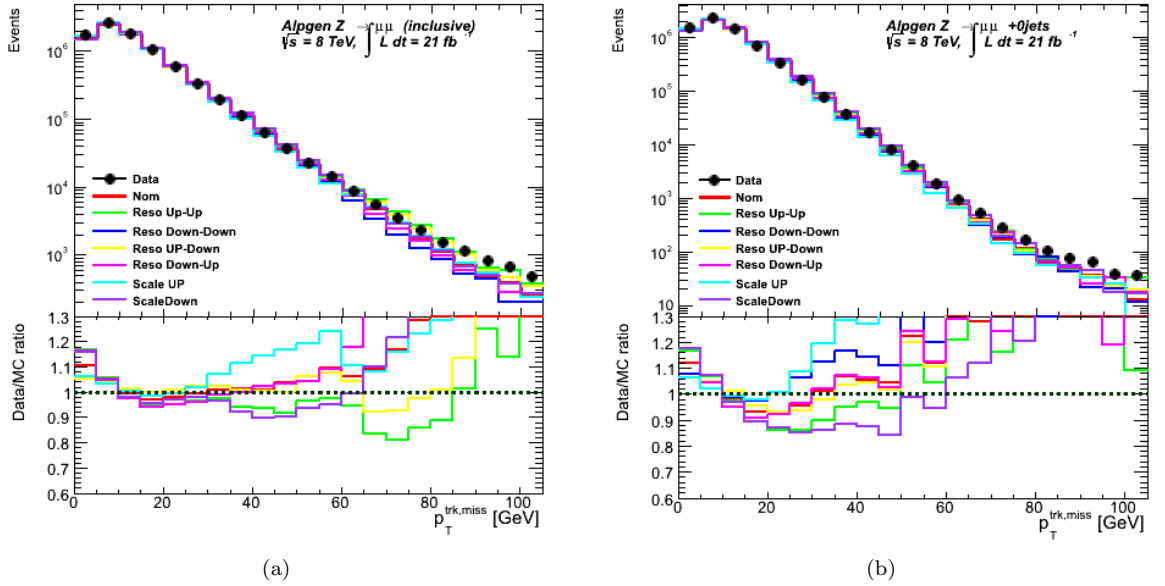


Figure 5.30: $\mathbf{p}_T^{\text{miss}}$ total systematic variations for $Z \rightarrow \mu\mu$ inclusive (a) and 0 jet (b) events. [F. Hariri]

Chapter 6

$\mathbf{p}_T^{\text{miss}}$ in Physics Analyses and Future Developments

The development of the track-based missing transverse momentum has been an important extension for the ATLAS $\mathbf{E}_T^{\text{miss}}$ reconstruction group, providing the various analyses with extra, complementary variables against which event selections can be made, as well as acting as a stepping stone towards a more pileup-stable version of the $\mathbf{E}_T^{\text{miss}}$. Here we provide a short overview of the use of $\mathbf{p}_T^{\text{miss}}$ in some analyses, and briefly introduce the concept of the track-based soft term in the standard $\mathbf{E}_T^{\text{miss}}$ reconstruction algorithm.

6.1 $\mathbf{p}_T^{\text{miss}}$ in ATLAS Physics Analyses

6.1.1 $\mathbf{p}_T^{\text{miss}}$ in the $H \rightarrow WW$ analysis

The first published use for the track-based missing transverse momentum in an ATLAS physics analysis was in late summer 2012, where the inclusion of the $\mathbf{p}_T^{\text{miss}}$ in the (0 and 1 jet) $H \rightarrow WW$ same-flavour analysis channel was able to be considered [67]. This channel had been excluded thus far for

8 TeV data owing to the large Drell-Yan background and degraded $\mathbf{E}_T^{\text{miss}}$ resolution from the increase in pileup in 2012. The ATLAS $H \rightarrow WW$ Run 1 legacy paper, just published, now measures the cross section for both the gluon-gluon fusion (ggF) and vector boson fusion (VBF) Higgs production mechanisms¹ covering both the same- and different-flavour channels [68].

The $H \rightarrow WW$ decays are identified by two oppositely-charged high $\mathbf{p}_T$ leptons, with real $\mathbf{E}_T^{\text{miss}}$ from the two neutrinos. Each W boson can decay to either an electron or a muon² but when the two leptons have the same flavour (i.e. in the ee or $\mu\mu$ case) then the $Z + \text{jets}$ production becomes a prohibitively large source of background. In the $e\mu$ and μe channels, the dominant background comes from the $\tau\tau$ decay channel where the τ 's decay leptonically, which has a smaller contribution overall. One can reduce the contribution from these backgrounds by requiring the presence of a significant amount of relative $\mathbf{E}_{T,\text{rel}}^{\text{miss}}$, where $\mathbf{E}_{T,\text{rel}}^{\text{miss}}$ is defined by

$$\mathbf{E}_{T,\text{rel}}^{\text{miss}} = \begin{cases} \mathbf{E}_T^{\text{miss}} & \text{if } \Delta\phi \geq \pi/2 \\ \mathbf{E}_T^{\text{miss}} \sin \Delta\phi & \text{if } \Delta\phi < \pi/2 \end{cases} \quad (6.1)$$

and $\Delta\phi$ is the difference in azimuthal direction between the $\mathbf{E}_T^{\text{miss}}$ and the nearest lepton or jet. A cut on $\mathbf{E}_{T,\text{rel}}^{\text{miss}} > 45$ GeV was sufficient in 2011 [69], but in 2012, with the increased Z background and decreased $\mathbf{E}_T^{\text{miss}}$ resolution, raising the cut threshold decreased the signal efficiency significantly. However, in Drell-Yan events the nominal $\mathbf{p}_T^{\text{miss}}$ tends to be aligned along the direction of the jets, while in signal events the alignment remains in the direction of the neutrinos. Incorporating a cut on $\mathbf{p}_{T,\text{rel}}^{\text{miss}} > 40$ (35) GeV in the event selections for the same-flavour 0 (1) jet ggF-enriched category therefore reduces the Drell-Yan background to a manageable level.

The object-corrected $\mathbf{p}_T^{\text{miss}}$ is also used in the $H \rightarrow WW$ analysis, for event preselection in the ggF-enriched different-flavour categories (for all jet multiplicities) as well as to reject Drell-Yan background in the same-flavour VBF-enriched category. Figure 6.1 shows the $\mathbf{E}_{T,\text{rel}}^{\text{miss}}$ and $\mathbf{p}_T^{\text{miss}}$ data and background distributions for the ≤ 1 jet same-flavour, and 0 and 1 jet different-flavour categories, marking the lower threshold value for the cut on each distribution to reduce the lower-peaking Drell-Yan background in each case (note that the distribution in figure 6.1 (a) is before the relevant cut on $\mathbf{p}_{T,\text{rel}}^{\text{miss}}$ as described above). A summary of the full set of selections per category are given in table IV in [68]).

¹See the glossary on page 129 for a short description of the Higgs production channels, as well as the Higgs section in appendix A.

²Or a tau lepton, but this decay channel is not considered in the analysis.

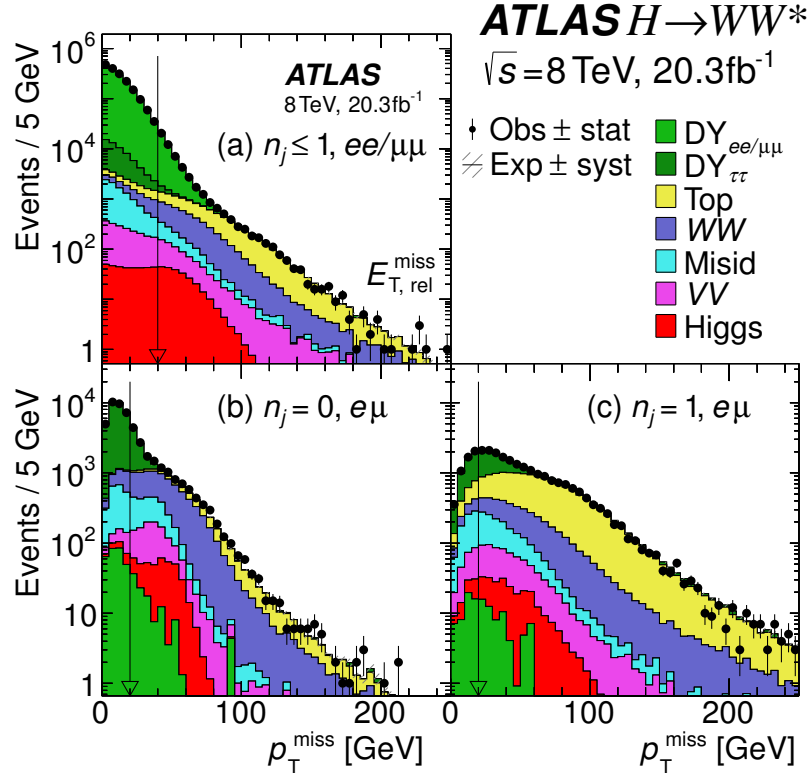


Figure 6.1: $\mathbf{E}_{T,\text{rel}}^{\text{miss}}$ (a) and object-corrected $\mathbf{p}_T^{\text{miss}}$ (b,c) distributions used for event preselection in the $H \rightarrow WW \leq 1$ jet same-flavour (a), and 0 jet (b) or 1 jet (c) different-flavour categories respectively. The Monte Carlo background composition shows the dominant DY backgrounds peaking at low values, and the arrows mark the lower threshold of the selection requirements. [68]

The $H \rightarrow WW$ signal yield in the ggF analysis is obtained from a direct fit to the transverse mass ($\mathbf{m}_T$) distribution for each category (in the VBF analysis the $\mathbf{m}_T$ distribution is one of the inputs to the BDT distribution used to fit for the signal yield). Because of the neutrinos from the W boson decay it is not possible to fully reconstruct the invariant mass of the final state, so the $\mathbf{m}_T$ is calculated as

$$\mathbf{m}_T = \sqrt{(E_T^{\ell\ell} + p_T^{\nu\nu})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\nu\nu}|^2} \quad (6.2)$$

where $E_T^{\ell\ell} = \sqrt{(\mathbf{p}_T^{\ell\ell})^2 + (m_{\ell\ell})^2}$, $\mathbf{p}_T^{\ell\ell}$ ($\mathbf{p}_T^{\nu\nu}$) is the vector sum of the lepton (neutrino) transverse momenta, and $p_T^{\ell\ell}$ ($p_T^{\nu\nu}$) is its modulus. Since only the leptons are detected, the $\mathbf{p}_T^{\nu\nu}$ (and $p_T^{\nu\nu}$) is therefore obtained from the measurement of the $\mathbf{E}_T^{\text{miss}}$ or $\mathbf{p}_T^{\text{miss}}$.

A comparison was done for the $\mathbf{m}_T$ reconstruction using both the $\mathbf{E}_T^{\text{miss}}$ and object-corrected $\mathbf{p}_T^{\text{miss}}$, and it was found that the $\mathbf{p}_T^{\text{miss}}$ improved the signal resolution considerably, reducing the r.m.s.

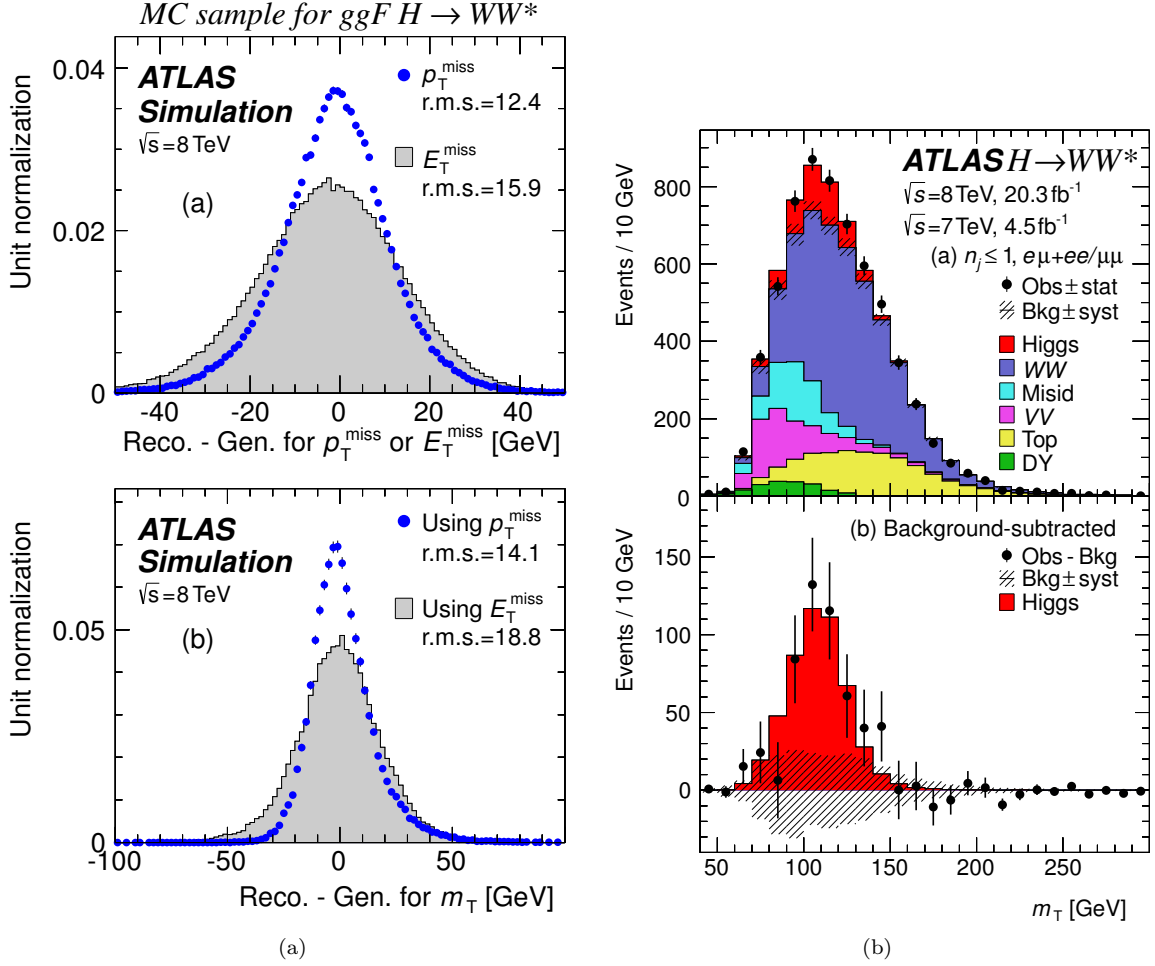


Figure 6.2: (a) Resolutions of the $\mathbf{E}_T^{\text{miss}}$ and object-corrected $\mathbf{p}_T^{\text{miss}}$ distributions (top), and the $\mathbf{m}_T$ calculated using the $\mathbf{E}_T^{\text{miss}}$ or object-corrected $\mathbf{p}_T^{\text{miss}}$ (bottom) for the $ggF H \rightarrow WW$ signal Monte Carlo sample in the 0 jet category.

(b) Post-fit combined $\mathbf{m}_T$ distributions for the 0 and 1 jet channels for both same- and different-flavour analyses, showing both the full backgrounds (top) and the background-subtracted distribution (bottom), with the expected signal from a 125 GeV Higgs. The object-corrected $\mathbf{p}_T^{\text{miss}}$ is used for the $\mathbf{m}_T$ calculation. [68]

of the $\mathbf{m}_T$ distribution from 19 to 14 GeV as shown in figure 6.2 (a). The improved resolution significantly increases the discrimination between signal and certain background processes, and the object-corrected $\mathbf{p}_T^{\text{miss}}$ is therefore used for the $\mathbf{m}_T$ calculation in all channels in the analysis. The post-fit $\mathbf{m}_T$ distributions for the combined 0 and 1 jet channels are shown in the top distribution in figure 6.2 (b), and the residual background-subtracted $\mathbf{m}_T$ distribution is shown below.

6.1.2 $\mathbf{p}_T^{\text{miss}}$ in the $H \rightarrow b\bar{b}$ analysis

At 57.7%, $H \rightarrow b\bar{b}$ has the highest branching ratio of all Higgs decays for a 125 GeV Higgs boson, but only the associated production channels are feasible analyses at hadron colliders owing to the large multijet background. ATLAS considers the VH and $t\bar{t}H$ production channels separately, and in the $t\bar{t}H \rightarrow b\bar{b}$ analysis, no requirement on the $\mathbf{E}_T^{\text{miss}}$ or $\mathbf{p}_T^{\text{miss}}$ is made at all, since, after all the event selections have been applied, the selected sample is dominated by $t\bar{t}+$ jets where such conditions are ineffective.

The $VH \rightarrow b\bar{b}$ analysis [70] covers both 2011 and 2012 LHC data following cut-based and multivariate approaches (for the different years respectively). Events are categorised by the number of high $\mathbf{p}_T$ isolated leptons in the event, into 0,1, or 2 lepton channels depending on the vector boson decay channel: $Z \rightarrow \nu\nu$, $W \rightarrow \ell\nu$, and $Z \rightarrow \ell\ell$. For the $\mathbf{p}_T^{\text{miss}}$ the focus is on the 0 lepton analysis, where the event signature is exactly two heavy-flavour-tagged jets [71] in the event, with a large amount of $\mathbf{E}_T^{\text{miss}}$ ($\mathbf{E}_T^{\text{miss}} > 120$ GeV). The $\mathbf{p}_T^{\text{miss}}$ is used here to suppress the large multijet background in both cut-based and multivariate versions of the analysis, with both a cut on its magnitude ($\mathbf{p}_T^{\text{miss}} > 30$ GeV), as well as a tight requirement on the $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ azimuthal directions ($\Delta\phi < \frac{\pi}{2}$) to suppress events with fake $\mathbf{E}_T^{\text{miss}}$. A detailed summary of the selections for their various categories is given in table 2 of [70].

6.1.3 Photons in $\mathbf{p}_T^{\text{miss}}$

The $\mathbf{p}_T^{\text{miss}}$ performs very well in events where the hard objects leave tracks, such as leptons (or jets, in the object-corrected version). However the physics program of ATLAS spans more than just final states with leptonic and hadronic decays. Indeed, the $H \rightarrow \gamma\gamma$ analysis requires two high $\mathbf{p}_T$ photons in the final state, an event signature that certainly would not call for the use of $\mathbf{p}_T^{\text{miss}}$ at first glance unless, of course, one could add the photon $\mathbf{p}_T$ to the $\mathbf{p}_T^{\text{miss}}$ (much in the same way as one does for the object-corrected version). Such a prospect is in fact feasible, and a study was done in cooperation with the ATLAS $H \rightarrow \gamma\gamma$ analysis group to form a version of the $\mathbf{p}_T^{\text{miss}}$ that included the two photons from the Higgs decay. In the end, the $\mathbf{p}_T^{\text{miss}}$ was not used in the analysis, but some

of the elements that had to be considered were interesting, and so a short overview of the method is given here.

The main issue with the photon analysis was with the vertex selection, as for a significant number of events the hard $\mathbf{p}_T$ objects were none other than the two photons from the Higgs decay, and therefore the automatic selection of the signal vertex as the one with the highest $\sum(p_T^{\text{track}})^2$ does not apply. In the analysis, a complex photon pointing algorithm is employed, using the longitudinal separation of the ATLAS calorimeters to provide a measure of the photon trajectory (tracks from photon conversions³ are also used to provide information of the conversion point if the tracks have hits in the silicon detectors). An artificial neural network [72] combines the photon pointing information with a number of vertex-related quantities, matching the production point of the two photons to one of the reconstructed primary vertices within 0.3 mm with 82% efficiency [73].

The $\mathbf{p}_T^{\text{miss}}$ can then be calculated using the negative vectorial sum of all the tracks associated with this diphoton vertex following the standard selections as detailed before, but with the values for d_0 and z_0 recalculated for the signal vertex of note, not the standard (ie 0th) primary vertex. The $\mathbf{p}_T$ of the signal photons are then added, and if the photons underwent a conversion (pair production) then any track⁴ from the conversion that passed the track selections is removed to avoid overlap.

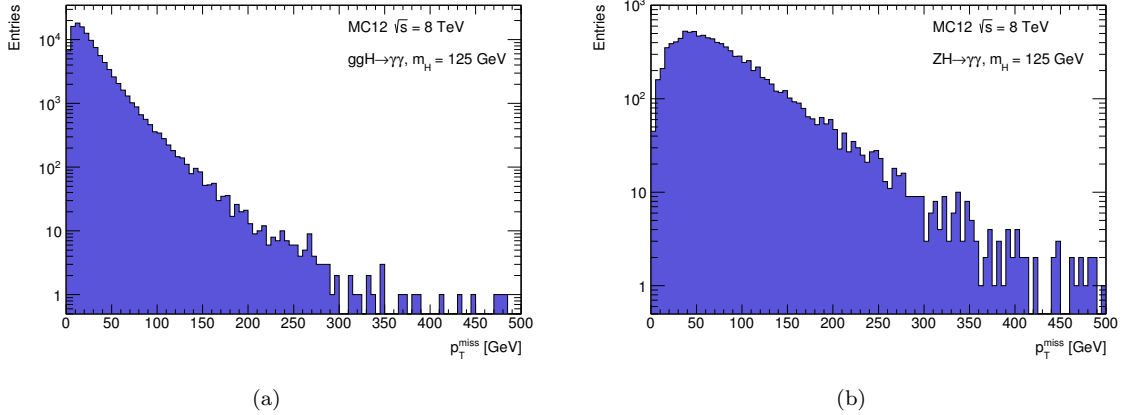


Figure 6.3: $\mathbf{p}_T^{\text{miss}}$ distributions in ggH (a) and ZH (b) events, where the Higgs decays to two high $\mathbf{p}_T$ photons which are included in the $\mathbf{p}_T^{\text{miss}}$. In the ZH case, the Z decays invisibly, leaving a signal of large missing transverse momentum.

³Photon pair production.

⁴Two charged particles are produced, but depending on their energies and orientations it is not a given that both tracks are reconstructed.

In the $H \rightarrow \gamma\gamma$ analysis, events that pass selection criteria are divided into 14 categories that cover VH-enriched, VBF-enriched, and ggF-enriched selections [73]. Of particular interest is the category with $\mathbf{E}_T^{\text{miss}}$, W or Z associated production where the W decays leptonically, or the Z decays to neutrinos, in contrast to the ggF category which is primarily $\mathbf{E}_T^{\text{miss}}$ -free. A brief study was done on $ggH \rightarrow \gamma\gamma$ and $ZH \rightarrow \gamma\gamma(Z \rightarrow \nu\nu)$ Monte Carlo simulation samples as a proof-of-concept for the $\mathbf{p}_T^{\text{miss}}$; figure 6.3 shows the $\mathbf{p}_T^{\text{miss}}$ distributions (with the photons added) in both ggH and ZH events. We can see the similarities between the distributions here and those of the $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ analyses, with the narrow peak near zero for the events without $\mathbf{E}_T^{\text{miss}}$ (ggH), and the shifted peak for the ZH events.

In addition, the difference in direction between the $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ can be calculated, as shown in figure 6.4 again for the ggH and ZH cases. A very strong correlation between the two quantities is seen for the ZH events, indicating that a cut on $\Delta\phi$ may be of help in separating ggH and ZH events. Not shown here, but also studied, was the resolution of the photon-corrected $\mathbf{p}_T^{\text{miss}}$, which retained its stability with pileup.

Ultimately the $\mathbf{p}_T^{\text{miss}}$ has not been used in the $H \rightarrow \gamma\gamma$ analysis up to now, however, the results are shown here as it may have the potential to be applied in future analyses, where a larger integrated luminosity may allow the analysis to split into individual analysis channels for each category (particularly $ZH \rightarrow \gamma\gamma$ with the invisible decay of the Z).

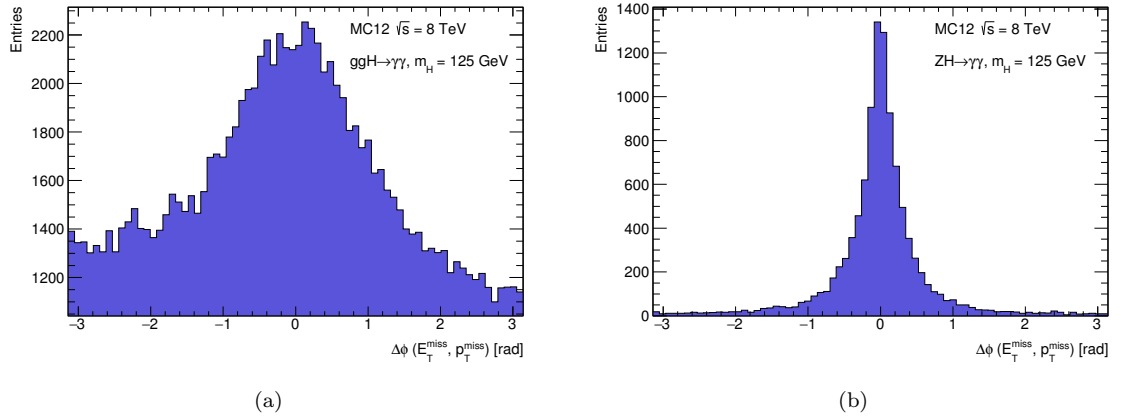


Figure 6.4: $\Delta\phi$ distributions between the $\mathbf{E}_T^{\text{miss}}$ and $\mathbf{p}_T^{\text{miss}}$ in ggH (a) and ZH (b) diphoton events, showing the increased correlation between the two quantities in events with real $\mathbf{E}_T^{\text{miss}}$.

6.2 Future Developments

While the $\mathbf{p}_T^{\text{miss}}$ in its current implementation shows good overall performance, and while the object-corrections have extended its potential use in events with jets, it of course is still limited in tracking detector acceptance and does not include objects such as photons, fully reconstructed tau leptons, and heavy flavour jets.⁵ In contrast, the $\mathbf{E}_T^{\text{miss}}$ is more inclusive of the hard objects, using the optimal identification algorithms and fully reconstructed momenta in the reconstruction, but it is also more sensitive to pileup, a nuisance that will only be exacerbated in the future runs.

The hard $\mathbf{p}_T$ objects are not where the issue with pileup lies, however. As we have seen, the majority of pileup interactions produce soft particles whose main contribution is to the $\mathbf{E}_T^{\text{miss}}$ soft term. Various methods [66, 74] have been employed in which either an estimate of the event energy density or tracking information is used to scale the calorimeter-cluster-based soft term contribution to the $\mathbf{E}_T^{\text{miss}}$ and hence mitigate the effect of pileup. While these methods showed improved performance with respect to pileup dependence, in other areas such as the $\mathbf{p}_T$ balance the method seemed to be overcorrected.

And so, drawing from the experience of these studies a synthesis of the $\mathbf{E}_T^{\text{miss}}$ and $\mathbf{p}_T^{\text{miss}}$ algorithms was formed, using the hard terms from the $\mathbf{E}_T^{\text{miss}}$, and with the soft term built solely from tracks originating from the primary vertex. This Track-based Soft Term $\mathbf{E}_T^{\text{miss}}$ is currently undergoing its final validation, and showing good pileup resilience while maintaining the original response of the $\mathbf{E}_T^{\text{miss}}$. It is the aim of the ATLAS $\mathbf{E}_T^{\text{miss}}$ group that this will be the default version of the $\mathbf{E}_T^{\text{miss}}$ reconstruction for the 2015 LHC run.

⁵Jets originating from the decay of a b quark may contain heavy flavour mesons which have a relatively long time of flight; these travel up to several mm in the detector before decaying, producing particles that come from a secondary, displaced vertex with respect to the first. Currently these displaced tracks are not taken into account if they fall outside of the $\mathbf{p}_T^{\text{miss}}$ impact parameter cuts, and future developments will focus on taking these b-jet tracks into account correctly.

Chapter 7

Conclusions and Outlook

The standard reconstruction of the missing transverse momentum in the ATLAS-recorded LHC Run 1 data uses a calorimeter-based measurement of $\mathbf{E}_T^{\text{miss}}$, a method which does well overall in its calculation of the magnitude and direction of any $\mathbf{E}_T^{\text{miss}}$ in the event, but which is affected by noise fluctuations and particle contributions from unrelated (pileup) vertices. To combat these unwanted effects, the vertexing ability of the ATLAS Inner Detector is put to use, where tracks from the hard (signal) vertex in the event can be separated from those originating from pileup collisions, with the advantage of one being able to make a pileup-independent measurement of the event activity. This led to the development of the $\mathbf{p}_T^{\text{miss}}$, a tracks-only approach to the $\mathbf{E}_T^{\text{miss}}$ reconstruction that can either stand alone or complement the calorimetric measurement.

The $\mathbf{E}_T^{\text{miss}}$ is traditionally built by summing terms composed of the (calorimeter-based) fully reconstructed and calibrated momentum measurements of hard objects¹ in the event, as well as a soft term built from unmatched calorimeter clusters, and the $\mathbf{p}_T^{\text{miss}}$ is not dissimilar. In the $\mathbf{p}_T^{\text{miss}}$ algorithms, however, the primary difference is that the soft term is comprised of only tracks from the signal vertex that are unmatched to any hard $\mathbf{p}_T$ objects in the event. By selecting good quality tracks through an optimised selection procedure we are thus able to reduce the contamination of the

¹Electrons, photons, tau leptons, jets and muons.

soft term by contributions from misreconstructed or non-signal-vertex-related particles, which helps to reduce the tails and improve the measurement of the signal missing transverse momentum.

For the object terms², two different approaches were developed. In the nominal approach, we once again take the tracks-only route, using just the track momentum as measured by the ID for the contribution from each object. This has the advantage of retaining the independence of the $\mathbf{p}_T^{\text{miss}}$ measurement from the calorimeter-based $\mathbf{E}_T^{\text{miss}}$, but as we saw can add fake $\mathbf{p}_T^{\text{miss}}$ in events with jets or when the electron radiates. The alternative is to use the full reconstruction of the object momentum - as used by the terms in the $\mathbf{E}_T^{\text{miss}}$ - which provides a more complete momentum measurement of the objects and better reconstruction of the scale of the event as a result.

A detailed investigation into the performance of the two algorithms has been performed, using $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ events from 8 TeV centre-of-mass proton-proton collisions during the LHC Run 1, recorded by the ATLAS detector in 2012. By comparing the behaviour of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ in the different event topologies, we have gained a good understanding of the functioning of the $\mathbf{p}_T^{\text{miss}}$ algorithm. In $Z \rightarrow \ell\ell$ events the $\mathbf{p}_T^{\text{miss}}$ is able to provide a good measurement with a small offset from zero as one would expect when there is no real $\mathbf{E}_T^{\text{miss}}$ in the event. In the $W \rightarrow \ell\nu$ events where there is real $\mathbf{E}_T^{\text{miss}}$, the peak in the $\mathbf{p}_T^{\text{miss}}$ distributions are subsequently shifted to account for the fraction of momentum that is carried by the undetected neutrino. In both cases, we saw that the nominal $\mathbf{p}_T^{\text{miss}}$ performed particularly well for events with no hard jets, but this degraded as the number of jets in the event or the jet $\mathbf{p}_T$ increased. In these cases, the $\mathbf{p}_T$ substitutions made for the object-corrected $\mathbf{p}_T^{\text{miss}}$ do well to recover the lost momentum due to neutral particles and out-of-acceptance jets, and improve the $\mathbf{p}_T^{\text{miss}}$ distributions to some degree.

The Monte Carlo simulations describe the data well in general. Some differences are observed in the various distributions, for example, in the tails of the distributions and perhaps most noticeably in the scalar sum of the reconstructed transverse momentum (Σp_T). This is an effect arising mostly from the fact that individual particle tracks from the underlying event are not well described by any Monte Carlo sample, though some do better than others.³ The tracks related to hard objects are well modelled, however. Some additional data-MC discrepancy is observed in the $W \rightarrow \ell\nu$ events due

²In the $\mathbf{p}_T^{\text{miss}}$, the objects considered are electrons, jets and muons (photons do not leave tracks, and tau leptons are essentially either electrons, muons or narrow jets).

³See appendix B.

to the presence of a background from QCD processes, which are not included in the MC simulation samples.

The resolution shows excellent stability with respect to pileup - possibly the greatest advantage of the $\mathbf{p}_T^{\text{miss}}$ measurement - with values of ~ 10 GeV in the electron channels for the nominal $\mathbf{p}_T^{\text{miss}}$, and ~ 7.5 GeV for the rest. Both the nominal and object-corrected versions of the $\mathbf{p}_T^{\text{miss}}$ show this stability, and agree with simulation well. The direction of the $\mathbf{p}_T^{\text{miss}}$ is also shown to be stable against pileup, a useful quantity one can use in conjunction with the $\mathbf{E}_T^{\text{miss}}$ direction in physics analyses to suppress backgrounds that fake an $\mathbf{E}_T^{\text{miss}}$ signal.

The projection of the $\mathbf{p}_T^{\text{miss}}$ along the Z boson direction in $Z \rightarrow \ell\ell$ events provides us with a good measure of the balance between the hard and soft terms in the $\mathbf{p}_T^{\text{miss}}$ calculation. Good agreement is seen between data and Monte Carlo, but a negative bias is observed, suggesting that the underlying event activity may be underestimated in the soft track term. For the nominal $\mathbf{p}_T^{\text{miss}}$ the bias decreases monotonically, a consequence of consistently missing the neutral contribution from jets. In $W \rightarrow \ell\nu$ events, the linearity of the $\mathbf{p}_T^{\text{miss}}$ measurements is compared to the true $\mathbf{E}_T^{\text{miss}}$ from the neutrino in MC simulation samples. The scale bias is seen again here for the nominal $\mathbf{p}_T^{\text{miss}}$, but the object-corrected $\mathbf{p}_T^{\text{miss}}$ shows only a 5% bias for values of the true $\mathbf{E}_T^{\text{miss}}$ above ~ 40 GeV. And finally, the reconstruction of the W transverse mass using $\mathbf{p}_T^{\text{miss}}$ also shows a good linearity and pileup dependence.

Overall, the study of the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ gives us confidence that our algorithms are able to describe the topology of hard scatter events with and without real $\mathbf{E}_T^{\text{miss}}$ well, and we have also gained insight as to what happens at the particle level in these types of events. As mentioned, the $\mathbf{p}_T^{\text{miss}}$ in various forms has already been used in a number of physics analyses, including Higgs searches and measurements on the Run 1 dataset. As we move into the second of the LHC's runs starting in early 2015, with increased energy and luminosity comes the complication of increased noise and pileup, and the $\mathbf{p}_T^{\text{miss}}$ track-based concept with its ability to reduce the overall effect of these is foreseen to assuage the issue to some degree.

The $\mathbf{p}_T^{\text{miss}}$ calculation at present contains a good selection of the hard $\mathbf{p}_T$ objects that typically emerge from the pp collisions: light leptons (electrons and muons) and jets from QCD hadronisation,

all objects whose charged particle tracks in the Inner Detector can act as the object's stand-alone momentum contribution. However, hard objects such as fully reconstructed photons, tau leptons and heavy flavour jets need to be included for the $\mathbf{p}_T^{\text{miss}}$ to be considered a completely universal measurement. Such an extension emerged from the results of the studies done here: a hybridised measurement of the missing transverse momentum created together by the $\mathbf{E}_T^{\text{miss}}$ and $\mathbf{p}_T^{\text{miss}}$ developers, which replaces the traditional calorimeter cluster-based soft term by a tracks-only soft term (TST) while maintaining the complete spread of reconstructed objects used in the $\mathbf{E}_T^{\text{miss}}$. This TST-based $\mathbf{E}_T^{\text{miss}}$ is undergoing final validation with good results overall, and is set to be the default version of the $\mathbf{E}_T^{\text{miss}}$ for the start of the ATLAS Run 2 datataking.

The missing transverse momentum is a vital quantity in collider physics analyses, used for a variety of reasons from event selections and background rejections, to control region estimation and mass reconstruction of decayed-particle systems. The prospects for a complete measurement need to be weighed against the associated disadvantages resulting from effects such as pileup, and the $\mathbf{p}_T^{\text{miss}}$ has shown to be a useful complement to the arsenal of reconstructed quantities used by the ATLAS collaboration in analyses. The study and development of the $\mathbf{p}_T^{\text{miss}}$ and $\mathbf{E}_T^{\text{miss}}$ will continue long into the future in order to provide the experiment with the best possible measurement of the event, and as we move into 2015 we look forward to the upcoming physics results with the Large Hadron Collider.

Appendix A

Development of the Standard Model

The (non-relativistic) Schrödinger equation describes quantum theory and atomic physics with high accuracy, but in elementary particle physics where relativistic effects need to be taken into account the model is not sufficient. Attempts to reconcile special relativity with quantum mechanics led to the existence of solutions with negative energy; this was considered a problem until Dirac [75] formulated his Lorentz-invariant version in 1928, expressed by the Lagrangian density (in natural units):

$$\mathcal{L} = i\bar{\Psi}\gamma_\mu\partial^\mu\Psi - m\bar{\Psi}\Psi \quad (\text{A.1})$$

with the corresponding wave equation for free spin- $\frac{1}{2}$ particles:

$$(\gamma^\mu p_\mu - m)\Psi(x) = 0 \quad (\text{A.2})$$

where γ^μ are the Dirac matrices and p_μ is the momentum operator $i\partial_\mu$. In this formalism, Ψ are four-component wave functions called spinors, allowing four solutions to the wave equation: two with positive energy, and two with negative energy. The issue with the negative energy solutions

was resolved by Dirac's reinterpretation of these states as antiparticles, and predicted the existence of the positron which was subsequently discovered by Anderson, Blackett and Ochialini in 1933.¹ For each energy, the two associated states give a natural representation of the two possible spin states of a spin- $\frac{1}{2}$ particle: spin up and spin down.

A.1 Quantum electrodynamics

The second quantisation of the Ψ fields allow for the creation and annihilation of particles, an integral requirement for a theory of elementary particles. Requiring gauge invariance of equation A.1 under the $U(1)$ transformation

$$\Psi(x) \rightarrow e^{i\alpha(x)}\Psi(x) \quad (\text{A.3})$$

gives us a Lagrangian density that is locally $U(1)$ gauge invariant:

$$\mathcal{L} = \bar{\Psi}(i\gamma_\mu\partial^\mu)\Psi + e\bar{\Psi}\gamma_\mu A^\mu\Psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (\text{A.4})$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. To preserve the local gauge symmetry a vector field A_μ needed to be introduced, and the term $e\bar{\Psi}\gamma_\mu A^\mu\Psi$ describes the interaction of the fermion field with this vector field. The second quantisation of these fields therefore provides us with a theory which describes the interaction of fermions via the exchange of the quanta of the A_μ field. Finally, the term $F_{\mu\nu}F^{\mu\nu}$ describes the kinetic energy (and possible self interaction) of the gauge field.

In this particular case, $F_{\mu\nu}F^{\mu\nu}$ has the same form as Maxwell's equations; this, taken with the fact that the associated gauge boson is massless (since no mass term $m^2 A_\mu A^\mu$ appears in the Lagrangian) implies that the Lagrangian in equation A.4 describes the theory of our most familiar force, Quantum Electrodynamics (QED), where the interactions between electrically charged fermions are mediated by massless photons [76, 9].

¹The discovery used a device called a cloud chamber, the earliest example of a particle detector that is able to record the tracks of charged particles as they move through the detector medium.

All processes in QED can be built from a set of eight single-vertex Feynman diagrams, each with an associated probability proportional to the strength of the fine structure constant α ,² and maintaining charge and energy conservation at each vertex. These diagrams may be combined in any order that preserves the conservation laws³ to obtain the interactions we observe in nature, and for each combination the overall contribution is of the order α^n , where n is the number of interaction vertices in the overall diagram. Feynman first introduced his diagrams as a method for solving problems in QED, though their principles are not restricted to this use, and they have proven to be invaluable assets in elementary particle field theory even today.

A.2 Quantum chromodynamics

To describe high energy hadronic collisions, the parton model was first proposed by Feynman in 1969 [77], stating that hadrons were composed of individual, charged, point-like constituents. A year earlier, Bjorken had proposed the scale invariance (“Bjorken scaling”) of the structure functions of electron-nucleon deep inelastic scattering, in strong contrast to elastic scattering which shows a strong energy dependence. This peculiar scaling behaviour was first observed in deep inelastic scattering (DIS) experiments at SLAC in 1969, and, together with the theories from Bjorken and Feynman, this led to the recognition of quarks as the actual elementary particles that make up the proton (and other hadrons) [78].⁴

However, the scaling in its original form was approximate, and there were small deviations not originally observed at the time (due to the range and resolution of the current experiments). Explicit perturbative calculations showed that scaling-breaking terms invariably appeared as order increased, though summing these terms led to an extremely large deviation from the scaling behaviour in all field theories that were known at the time, a noticeable contradiction from the data. This inspired the idea of asymptotic freedom: in an asymptotically free theory, where the effective coupling approaches

² $\alpha = \frac{1}{4\pi\epsilon_0} \frac{e^2}{\hbar c} \approx \frac{1}{137}$

³In some cases energy conservation may be violated through the exchange of virtual particles, but this is only allowed if it happens within a short enough period of time compatible with the uncertainty principle.

⁴Quarks were proposed by Gell-Mann [79] and Zweig [80] in 1964 as an explanation for the organised classification scheme of hadrons, although the concept of fractionally-charged objects was, at the time, repulsive, and quarks were considered nothing more than a useful mathematical construct for a few years. Even in his original paper, Gell-Mann wrote “a search for stable quarks... at the highest energy accelerators would help to reassure us of the nonexistence of real quarks.”

zero as the scale increases, mild scaling violations are possible. The culmination of the search for such a field theory is what we know of today as Quantum Chromodynamics (QCD), and it predicts the detailed violations of the scaling behaviour that have been fully confirmed with modern high energy experiments.

QCD is the field theory describing quarks, gluons, and their interactions, and has a fundamental gauge symmetry characterised by the non-abelian group $SU(3)$ with colour charge, a 3-valued quantum number (denoted $SU(3)_c$) [76]. The gauge invariance of QCD leads to an interesting consequence: in considering transformations of colour-charged quarks, the interaction term implies that the colour of the quark changes, which is only possible if the mediating particles (gluons) themselves carry colour. This, then, means that gluons can interact not only with quarks, but also with themselves, and it is this self-interaction that leads to the asymptotic freedom required by the theory,⁵ as well as other important consequences such as confinement.

A.2.1 Confinement, hadronisation, and jets at hadron colliders

Only colour singlet states can exist as free particles under $SU(3)_c$. These are classified under the catch-all name “hadrons”, and refer to either three bound valence quarks (baryons) or quark-antiquark pairs (mesons)⁶. The non-abelian nature of QCD and its resulting asymptotic freedom at small distance scales has a different consequence at large distances: if one tries to separate quarks from their bound states, as the distance between the quarks increases, so too does the potential energy of the gluon field between them. “Pulling” quarks further apart has the result of storing progressively more energy in the gluon field, and at a certain point (about 170 MeV) the energy stored in the field is greater than the mass-energy of a quark-antiquark pair. Thus, it becomes energetically favourable for the field to produce a new meson rather than release the original quark from its bound state, a process known as hadronisation.⁷

⁵In contrast to QED, the gluon self-coupling has an anti-screening effect, which makes the coupling weaker at short distances.

⁶The colour singlets are therefore either “red, green, blue” in the baryon case (as an analogy to white light), or “colour-anticolour” in the case of mesons.

⁷Another way of thinking about this is that adding enough energy into the system causes a pair of virtual sea quark pairs to become on-shell.

A consequence of confinement and hadronisation is that experimentally, single quarks and gluons never appear in our detectors. Yet, when considering scattering at inelastic scales, high energy quarks and gluons certainly are emitted in the process. As these move away from the interaction point they radiate, producing a shower of quarks and gluons which hadronise into the final state particles we observe as a tight cone of particles called a jet. In ATLAS, the MV1c b-tagging algorithm [71, 81, 82] may be used to identify jets originating from heavy flavour quark fragmentation compared to light quark or gluon jets, allowing some sensitivity to the original radiated parton from the scattering.

The evolution from high energy partons to the multiple collimated hadrons spans both perturbative and non-perturbative QCD in a process that is not fully understood even today. In the perturbative phase, high $\mathbf{p}_T$ partons are produced from the interaction. In the second (non-perturbative) phase, these partons start emitting gluons, which produce quark-antiquark pairs, which in turn emit more gluons. This process reduces the energy of the partons until they no longer have enough energy to withstand confinement⁸ and thus hadronise into a highly collimated shower of mesons and baryons. These are the final state particles we observe, eventually depositing most of their energy in the calorimeter.

Jets are common but important signatures in hadron colliders, providing a good tool for probing the hard interaction, although they can result from a variety of both hard and soft processes. The physics behind the jet production in each case is very different, and within ATLAS jets are considered well-defined only if their transverse momenta is above 20 GeV. Nevertheless, both hard and soft jets produce extra particles from the interaction that must be accounted for, and whose energies and momenta must be accurately measured in order to infer the energies and momenta of the initial high energy parton.

A.3 Electroweak symmetry breaking and the Higgs sector

The final key development for the Standard Model was that of the unification of the electromagnetic and weak theories, for which Glashow, Salam and Weinberg were awarded the Nobel prize in 1979. The unified theory was first proposed to solve problems associated with interactions where more

⁸Below about 1 GeV.

than one W boson was exchanged, such as in the reaction $e^+e^- \rightarrow \mu^+\mu^-$. Since these interactions are higher order their contributions are expected to be small, however theoretical predictions using the weak force alone produced infinite divergences. Only in the unified theory, when contributions mediated by the neutral Z and γ bosons are taken into account, do these divergences cancel, giving a finite, small contribution overall.

With the gauge invariance of the proposed symmetry structure $SU(2) \times U(1)$ comes the inclusion of two new vector fields: the isotriplet W_μ^i corresponding to the weak isospin field $SU(2)$ with coupling strength g , and a single field B_μ from the $U(1)$ weak hypercharge field with coupling g' . The first two components of W_μ^i correspond to the charged vector bosons W^+ and W^- (although the charged W's only appear after electroweak theory is broken, since electric charge isn't well defined until this point); however, in this scheme the neutral gauge bosons would be the the third component W^0 , and B^0 , rather than our experimentally-observed Z boson and photon.⁹ As an additional problem, again the inclusion of a mass term in the Lagrangian would break the gauge invariance of the model, meaning that the gauge bosons must all be massless, except in this particular case we knew that the W and Z bosons had mass.¹⁰

The solution to this problem came in 1964 with three separate, independent and almost simultaneous papers by Brout and Englert [83]; Higgs [84]; and Guralnik, Hagen, and Kibble [85], proposing the addition of a complex scalar field to the theory. If this scalar field had a non-zero vacuum expectation value it would not be invariant under gauge transformations, and the theory would no longer be gauge invariant. By Goldstone's theorem the resultant symmetry breaking would mean the appearance of massless Goldstone bosons in the theory [86]. However, the 1964 papers showed that if the field that causes the spontaneous symmetry breaking was combined with a gauge field, it would be the gauge bosons themselves that acquired the mass. Thus the "Higgs mechanism" as we know it today gives us the electroweak theory we are familiar with, including the massless photon, and the charged W and neutral Z bosons. However, only the massive spin-1 vector bosons acquire their mass through

⁹The issue here is that the W^0 would have the same mass as its charged components, against what we see in nature.

¹⁰Historically, the masses of the W and Z bosons came as a result of the unification condition $\frac{e}{2(2\varepsilon_0)^{1/2}} = g_W \sin \theta_W = g_Z \cos \theta_W$, and were predicted from the strengths of various interactions before the bosons were even discovered.

the Higgs mechanism in this way; spin- $\frac{1}{2}$ fermions instead obtain their mass through the Yukawa coupling between the Higgs and fermion fields.¹¹

A.3.1 The Higgs boson

It was the addition of a single line at the end of his 1964 paper that made Higgs stand out from the rest, where he wrote that “an essential feature” of the theory was the implied existence of a massive scalar boson - the “leftover” Goldstone boson from the symmetry breaking - and as a result it is after Higgs that we name the field and its associated particle. After almost half a century, the discovery of a new particle consistent with the Higgs boson of the Standard Model and with a mass around 125 GeV was announced by the ATLAS and CMS collaborations [87, 88], which (in what is possibly simultaneously the shortest and lengthiest time taken to award a prize) earned Higgs and Englert the 2013 Nobel prize in physics.

Within the framework of the Standard Model, the Higgs boson couples to particles with a strength proportional to their masses. There are four main production channels for the Higgs boson: gluon-gluon fusion (ggF), a process that proceeds through a top quark loop since the massless gluons do not couple directly to the Higgs field; vector boson fusion (VBF); associated production with a vector boson (VH)¹²; and associated production with a pair of top quarks (ttH). Of these, ggF is by far the dominant production channel at the LHC [89], though by selecting events based on the associated products of the interaction one is able to extract events resulting from the other production mechanisms with good purity.

At a mass of ~ 125 GeV, the Higgs boson’s dominant decays are to pairs of b quarks, W bosons, or Z bosons. However, the $b\bar{b}$ channel is an extremely difficult analysis due to the large background from QCD, and the mass resolution in the WW channel is poor owing to the presence of $\mathbf{E}_T^{\text{miss}}$. In contrast, the four lepton decay channel of $H \rightarrow ZZ$, while rare, provides a very clean experimental

¹¹Of course nothing is this “simple” in reality, and the neutrinos are glaring evidence of this. Since only left-handed neutrinos exist within the Standard Model, even with a Yukawa coupling they still remain massless. Adding the necessary framework to the SM to account for their nonzero (albeit small) mass is straightforward enough, if you can bear either the existence of a sterile right-handed neutrino field (not experimentally convincing thus far), or the requirement that neutrinos satisfy the Majorana equation (and its subsequent lepton number violation). Therefore, the neutrino masses remain an unsolved mystery today.

¹²also called Higgs-strahlung

signature, and the $\gamma\gamma$ channel has the advantage of large statistics with a signal of two isolated photons over a well-modeled background. It was for this reason that the primary search channels for the 2012 discovery were the ZZ and $\gamma\gamma$ channels, although current physics analyses have since switched their focus to precise measurements of the Higgs properties and couplings, using as many of the decay channels as are experimentally feasible.

A.4 Limitations of the Standard Model

The Standard Model was not designed to be a unified theory, and as such it has limitations. The fermion masses, mixing angles, gauge couplings and the Higgs vacuum expectation value are all parameters that must be determined empirically, rather than emerging naturally from the theory. One unknown feature is why the duplication of fermions into their three distinct generation exists, since all of our “everyday” matter is comprised solely of particles from the first generation. Furthermore, the SM does not address the mixing of neutrinos (and their non-zero masses) for which we have evidence, as well as the obvious omission of gravity, which becomes important at the Planck scale of 10^{19} GeV.

Then, of course, there is the Planck scale itself, and the vast difference between it and the particle mass scale.¹³ The SM gives no indication for this difference, but it is related to the relatively-low-but-not-quite-zero value of the Higgs field, which seems to require some very precise fine tuning to avoid the Planck scale where we would naïvely have expected the value to be; this is known as the hierarchy problem. And finally, we have the matter-antimatter asymmetry observed in the universe (and indeed, without which we wouldn’t have a universe at all), as well as candidates for dark matter or even an inkling about dark energy. Altogether these shortcomings confirm that the SM is not the final theory of particle physics, and various Beyond the Standard Model (BSM) extensions have been developed over the past few decades in order to provide a more complete theory of nature. The physics programme at the Large Hadron Collider probes all parts of the SM, as well as many of the extended sectors and BSM theories.

¹³Or, in other words, the vast difference in strength between the weak and gravitational forces

Appendix B

$\mathbf{p}_T^{\text{miss}}$ Reconstruction with Different MC Event Generators

As has been shown, the $\mathbf{p}_T^{\text{miss}}$ is generally well modelled in MC simulation samples. However, there are some cases in which the data is not well represented by the generator, and the $\mathbf{p}_T^{\text{miss}}$ seems to be more sensitive to these effects than the solely calorimeter-based $\mathbf{E}_T^{\text{miss}}$ measurement. Here we show various distributions from (mainly) $Z \rightarrow \mu\mu$ events¹ that play a role in the $\mathbf{p}_T^{\text{miss}}$ reconstruction, where the signal distributions were modelled by either AlpgenJimmy or PowhegPythia.

B.1 Jet Mismodelling

One of the main differences between the two generators is in their treatment of jets, where Powheg-Pythia takes a more inclusive approach using PDFs to predict the final-state partons, whereas AlpgenJimmy considers the individual partons in the interaction. As a result, the n_{jets} , jet $\mathbf{p}_T$ and jet η distributions are much better modeled by AlpgenJimmy, as can be seen in figures B.1 and B.2, which plays a large part in the overall good description of the $\mathbf{p}_T^{\text{miss}}$ in figure 5.14. However in the

¹Similar distributions are seen in the ee channel.

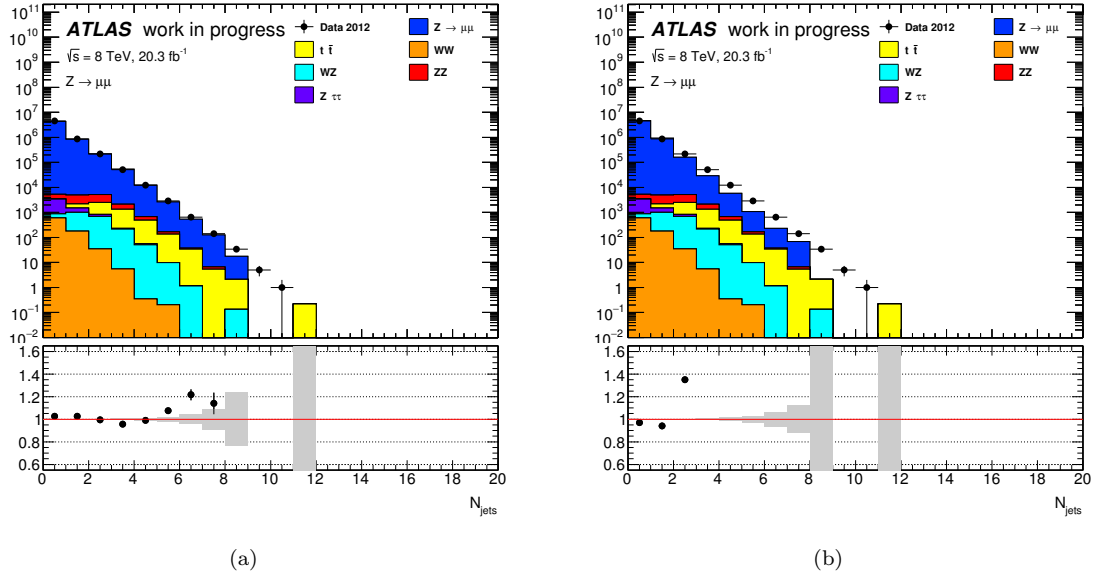


Figure B.1: Jet multiplicity distributions in $Z \rightarrow \mu\mu$ events for AlpgenJimmy (a) and PowhegPythia (b).

0 jet case, PowhegPythia has a better representation of the data in the core of the distributions, shown in figures B.3 and B.4 for the nominal and object-corrected $\mathbf{p}_T^{\text{miss}}$ respectively.

B.2 Underlying Event Mismodelling

Besides the jet mismodelling, another issue has an effect on the shape of the generated distributions: the description of the underlying event by the particular generator. The main difference between the calorimeter-based $\mathbf{E}_T^{\text{miss}}$ and the object-corrected $\mathbf{p}_T^{\text{miss}}$ is the use of tracks in the soft term, a difference that makes the $\mathbf{p}_T^{\text{miss}}$ much more sensitive to generator effects than the $\mathbf{E}_T^{\text{miss}}$. Compare, for example, the inclusive nominal $\mathbf{p}_T^{\text{miss}}$, object-corrected $\mathbf{p}_T^{\text{miss}}$, and $\mathbf{E}_T^{\text{miss}}$ distributions in figure B.5, where the agreement between data and MC is especially good for the $\mathbf{E}_T^{\text{miss}}$ using PowhegPythia. The effect is even more noticeable in the Σp_T distributions in figure B.6 where the AlpgenJimmy sample has much better description in the tail compared to the disastrous PowhegPythia, though the effect is also visible in the core of the distributions. This is because the Σp_T , being a scalar quantity, is much more sensitive to differences in the number of charged particles produced in the interaction and their individual momenta. Again, the ΣE_T distributions are shown for comparison,

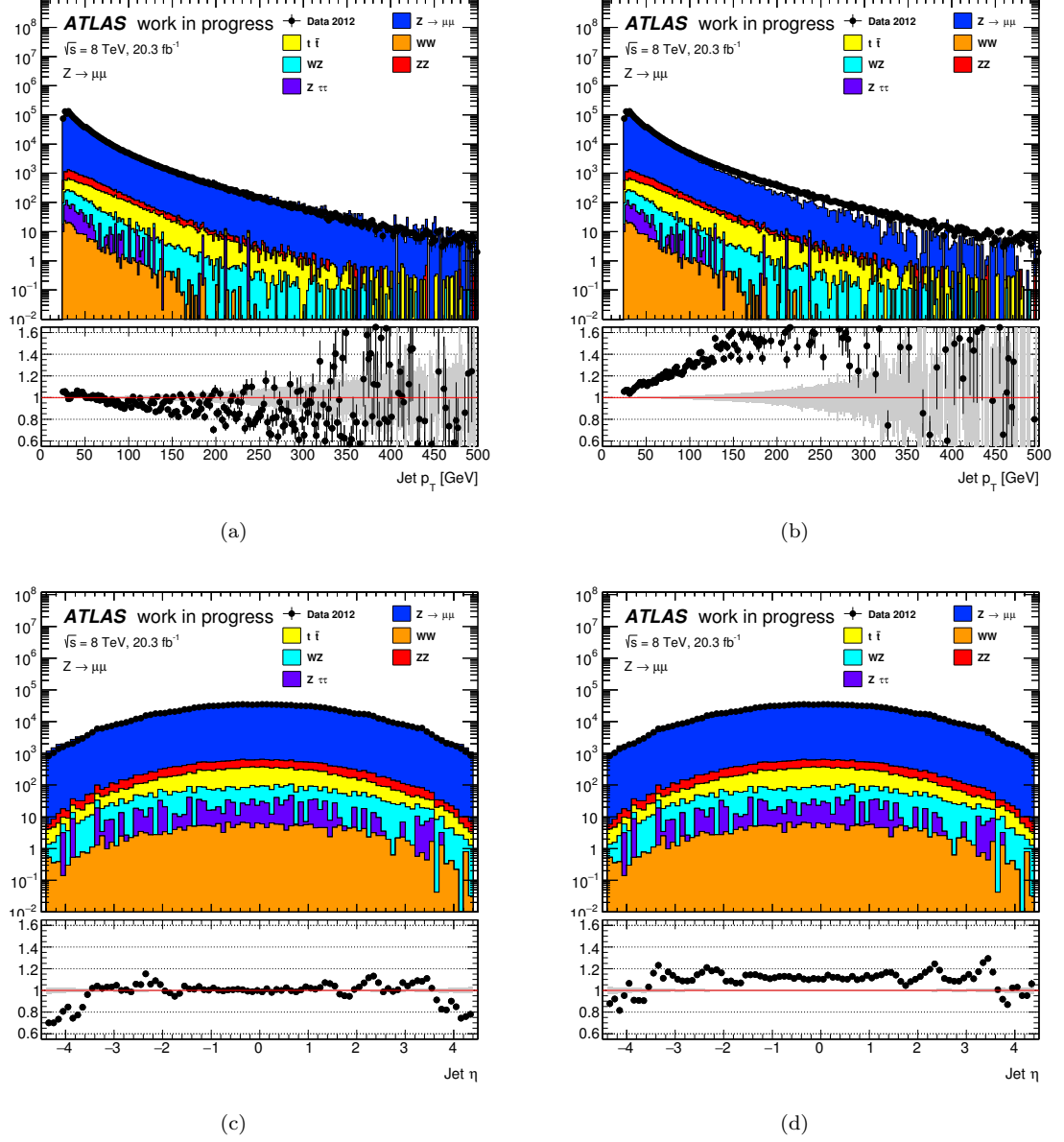


Figure B.2: Jet p_T (top) and η (bottom) distributions in $Z \rightarrow \mu\mu$ events for AlpGenJimmy (left) and PowhegPythia (right).

and the better MC description of the E_T^{miss} and ΣE_T distributions have two obvious sources: better modelling of the energy information of the interaction rather than of individual particles, as well as the fact that any effect is washed out somewhat by pileup.

As a final study, we show the distributions of the individual soft, jet and muon terms for $Z \rightarrow \mu\mu$ events and the electron term in $Z \rightarrow ee$ events, that make up the p_T^{miss} in figures B.7, B.8, B.9,

and B.10 respectively. Whereas the hard objects have generally well modelled descriptions for both the track-only and fully reconstructed cases, it is clear that it is in the soft term where the generators let us down. These results show that while we are able to make very good QCD predictions at higher energies, it is clear that we do not yet have a full understanding of what is happening at the non-perturbative scale, and, that it is becoming important even for high energy analyses that we ought to.

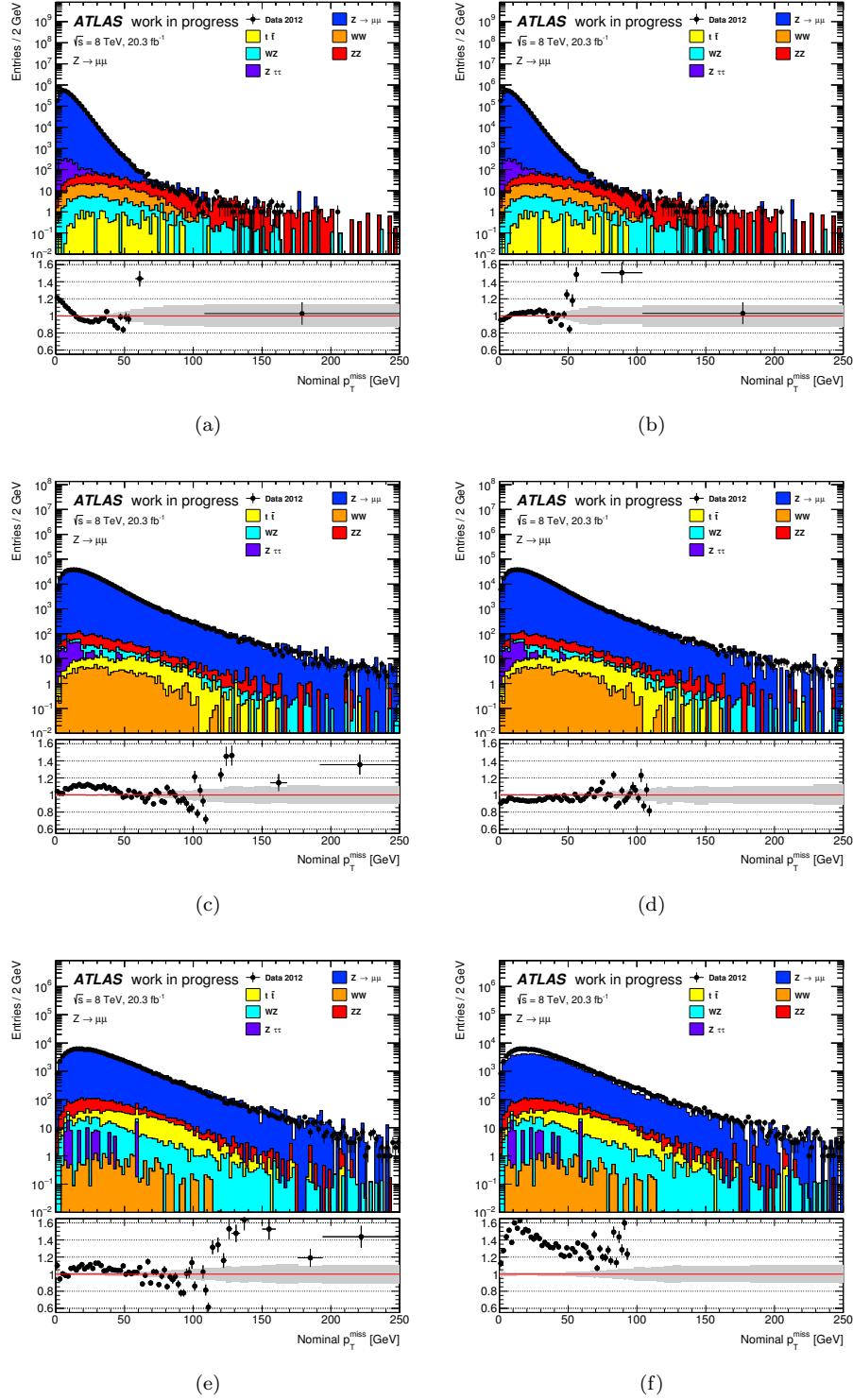


Figure B.3: Nominal p_T^{miss} 0 (top), 1 (middle), and 2 (bottom) jet distributions in $Z \rightarrow \mu\mu$ events for ALPGENJIMMY (left) and POWHEGPYTHIA (right).

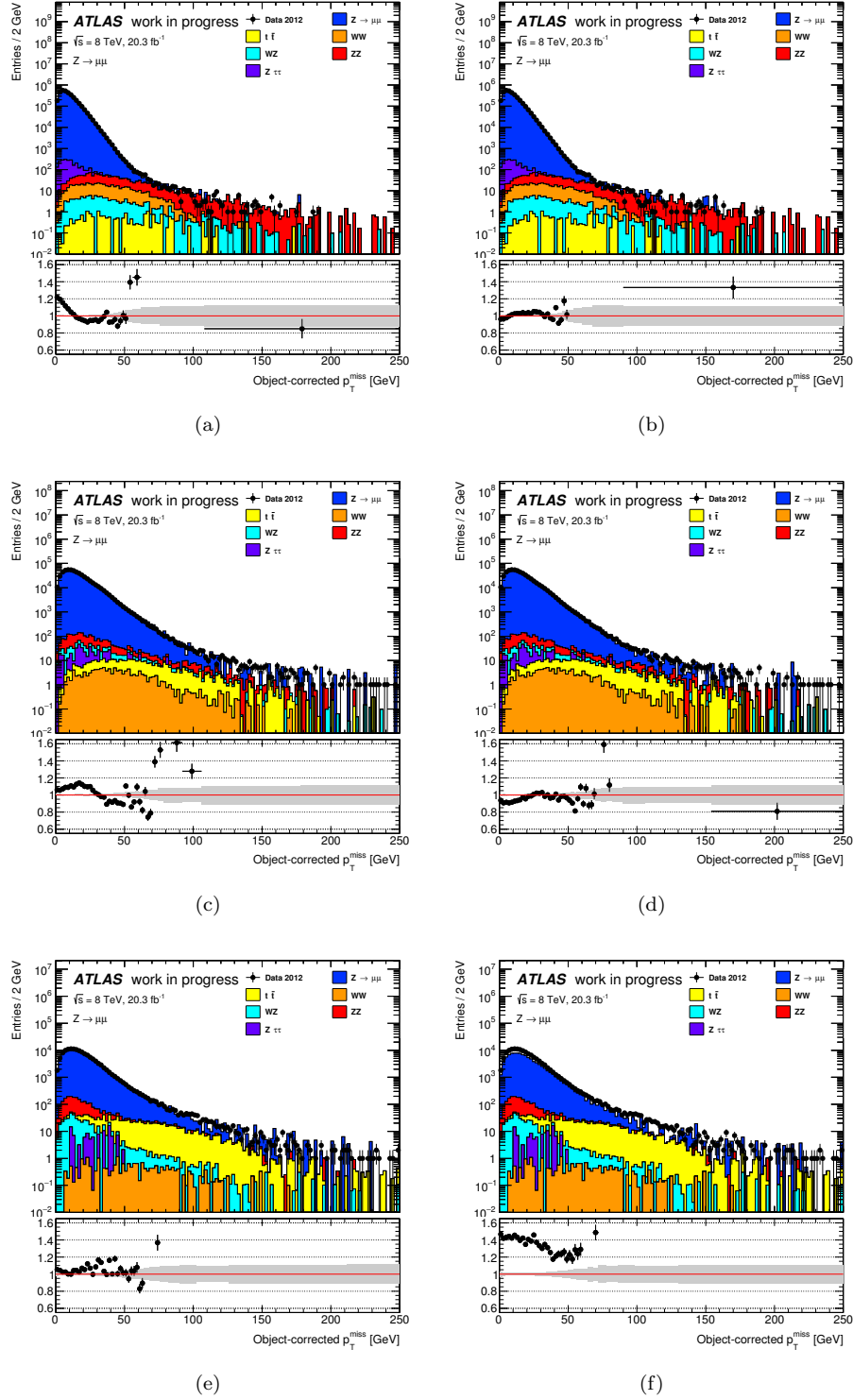


Figure B.4: Object-corrected p_T^{miss} 0 (top), 1 (middle), and 2 (bottom) jet distributions in $Z \rightarrow \mu\mu$ events for AlpgenJimmy (left) and PowhegPythia (right).

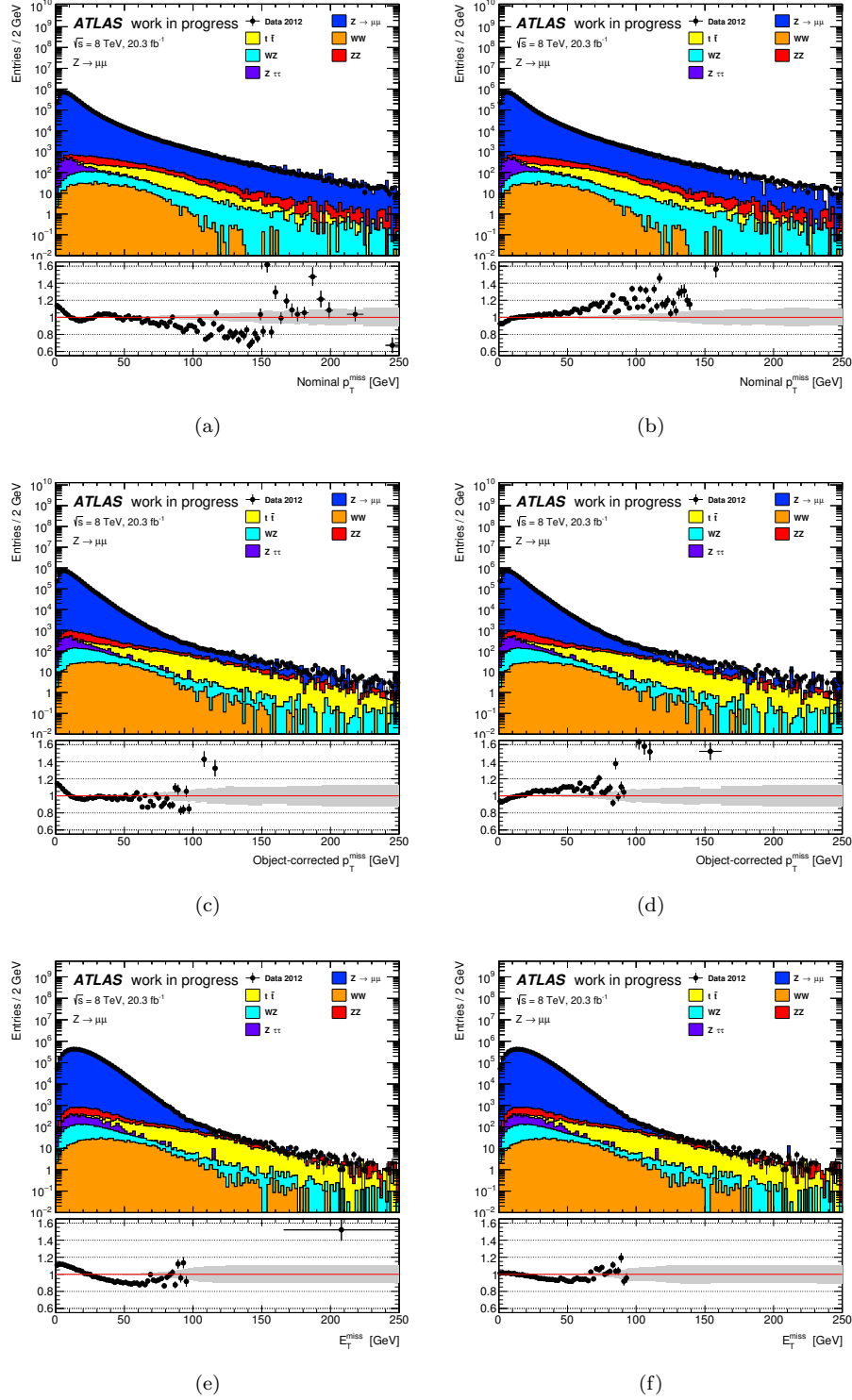


Figure B.5: Nominal p_T^{miss} (top), object-corrected p_T^{miss} (middle), and E_T^{miss} (bottom) distributions in $Z \rightarrow \mu\mu$ events for AlpgenJimmy (left) and PowhegPythia (right).

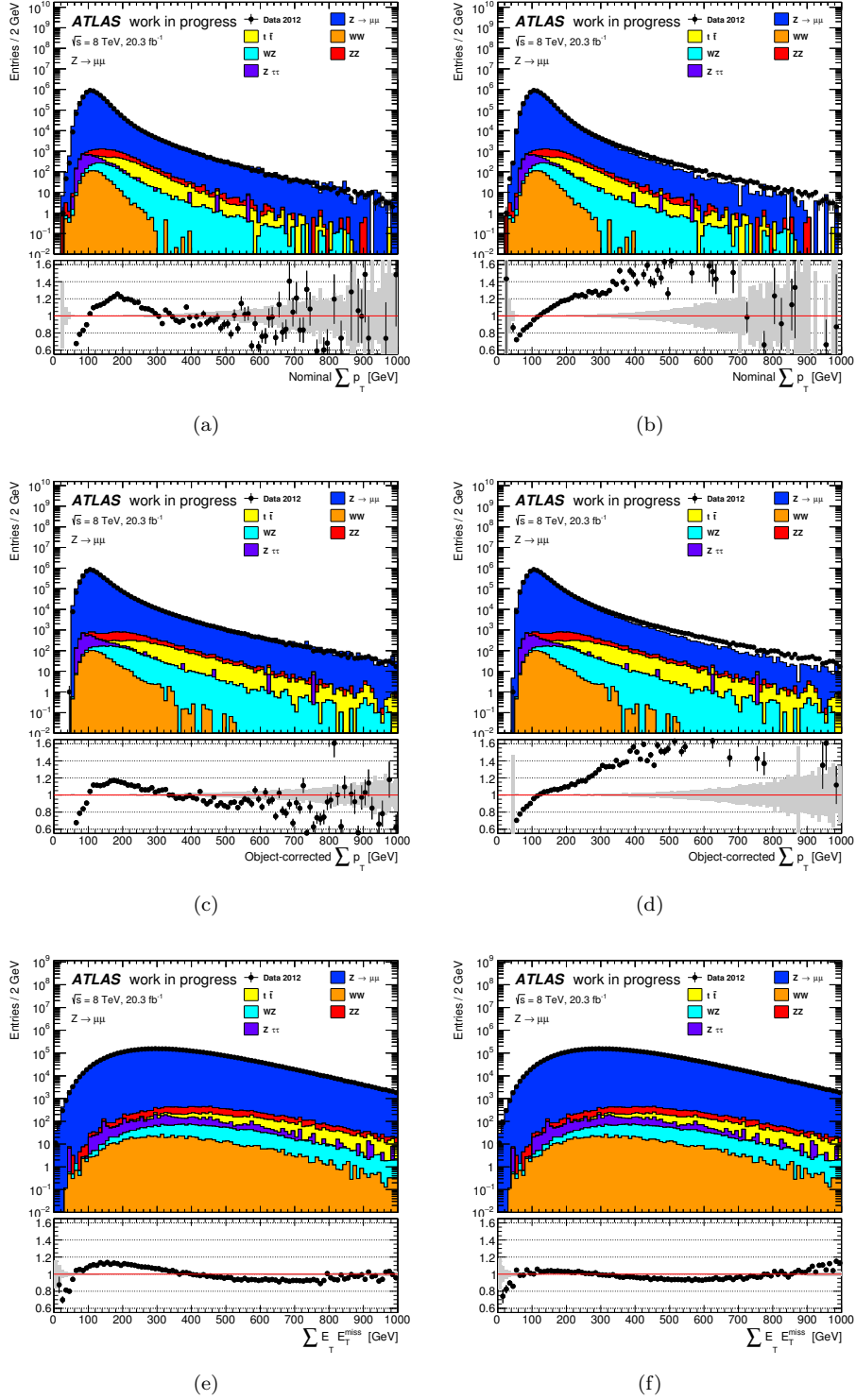


Figure B.6: Nominal Σp_T (top), object-corrected Σp_T (middle), and ΣE_T (bottom) distributions in $Z \rightarrow \mu\mu$ events for AlpgenJimmy (left) and PowhegPythia (right).

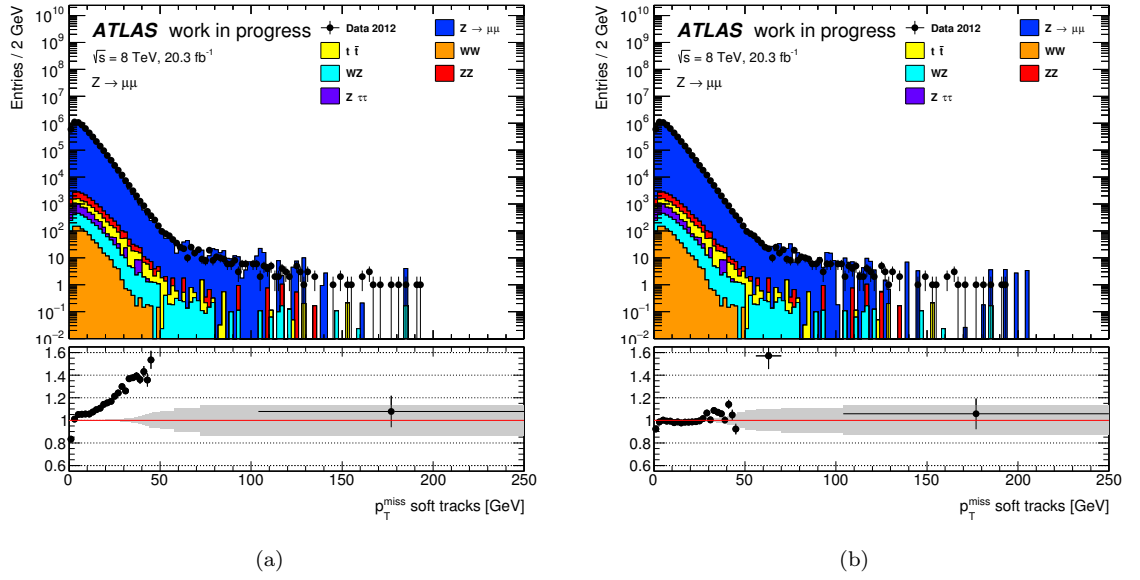


Figure B.7: Soft term modelling in the p_T^{miss} , for AlpgenJimmy (a) and PowhegPythia (b).

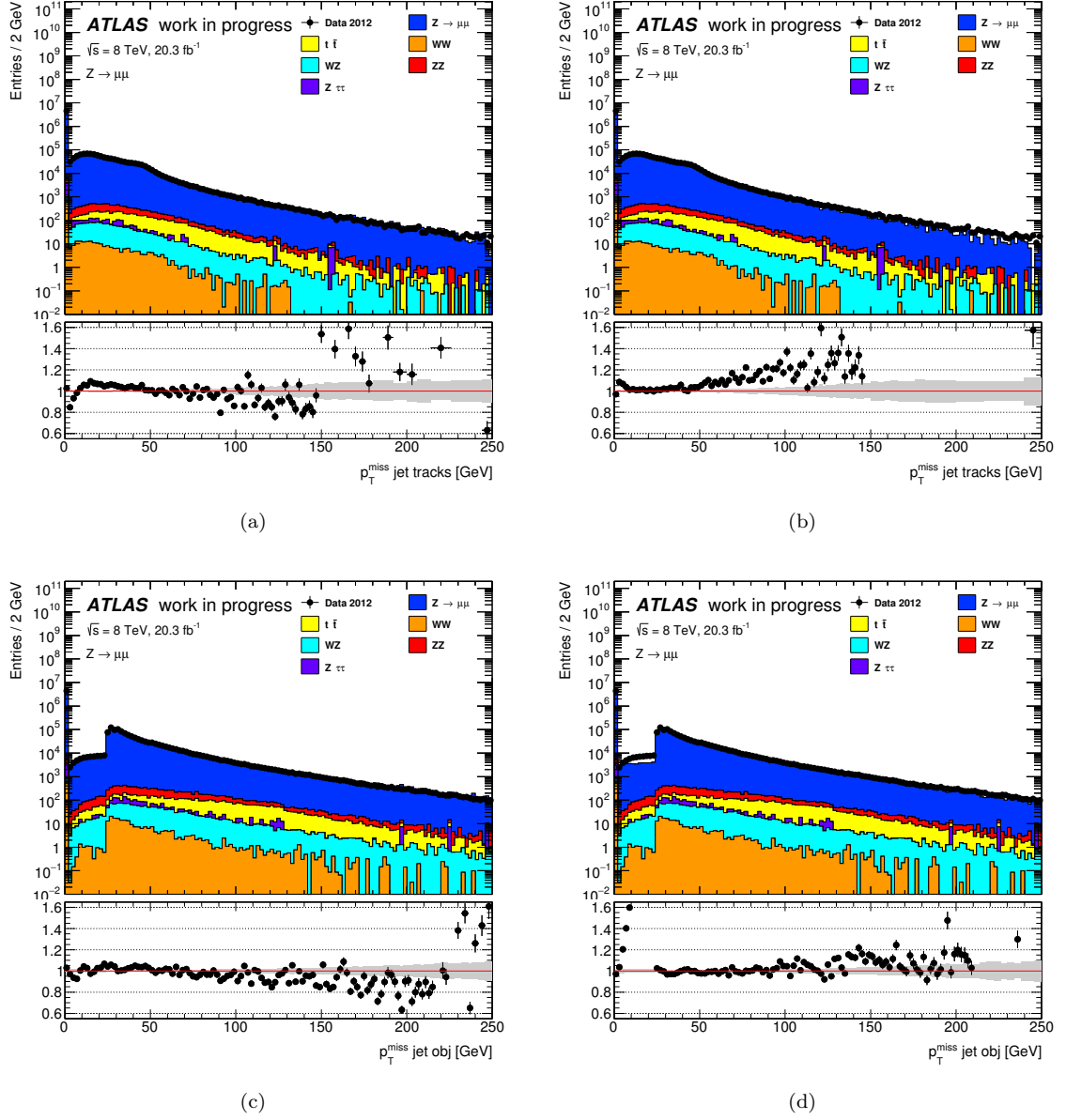


Figure B.8: Jet term modelling in the nominal (top) and object-corrected (bottom) p_T^{miss} , for AlpgenJimmy (left) and PowhegPythia (right).

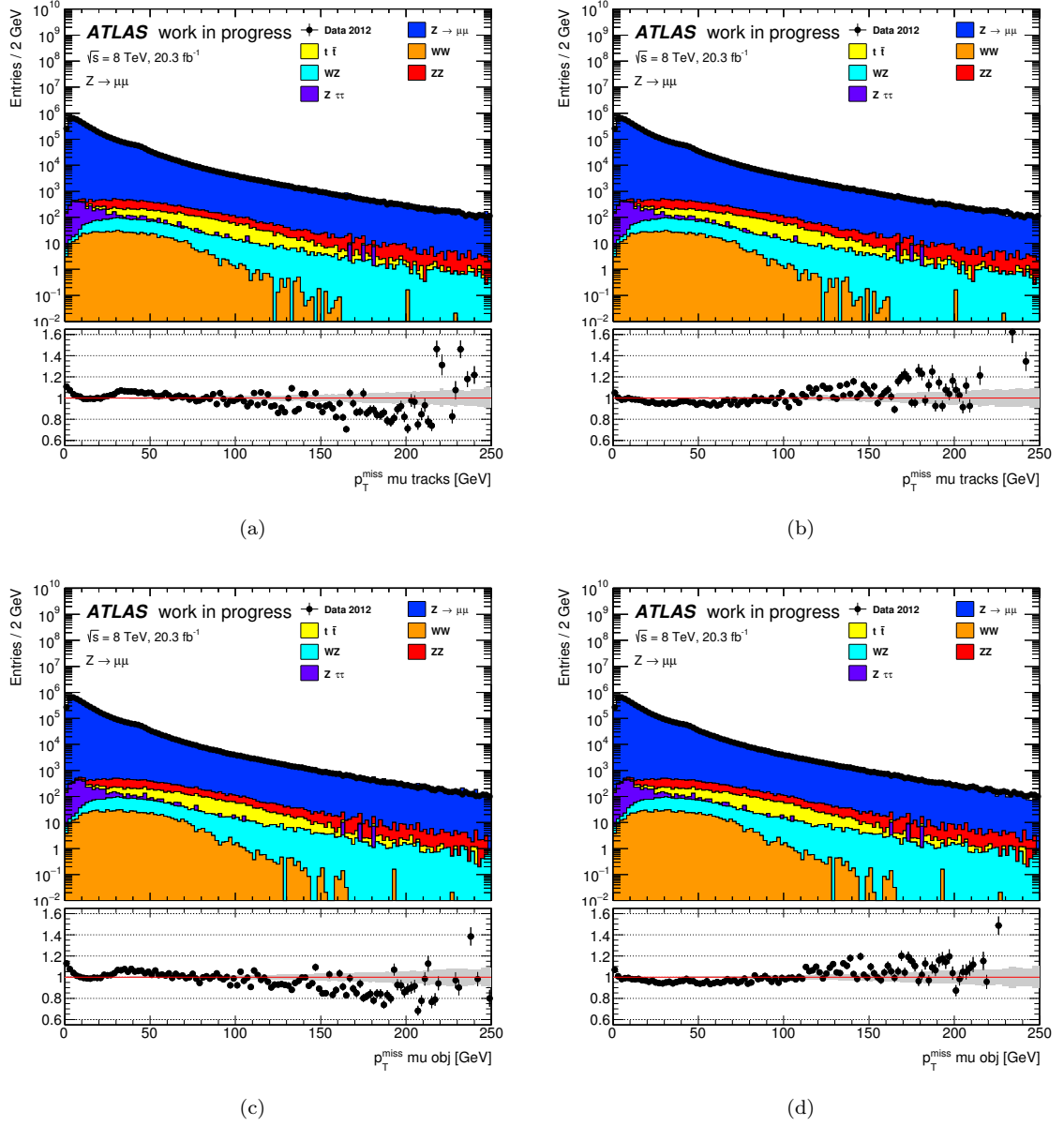


Figure B.9: Muon term modelling in the nominal (top) and object-corrected (bottom) p_T^{miss} , for AlpgenJimmy (left) and PowhegPythia (right).

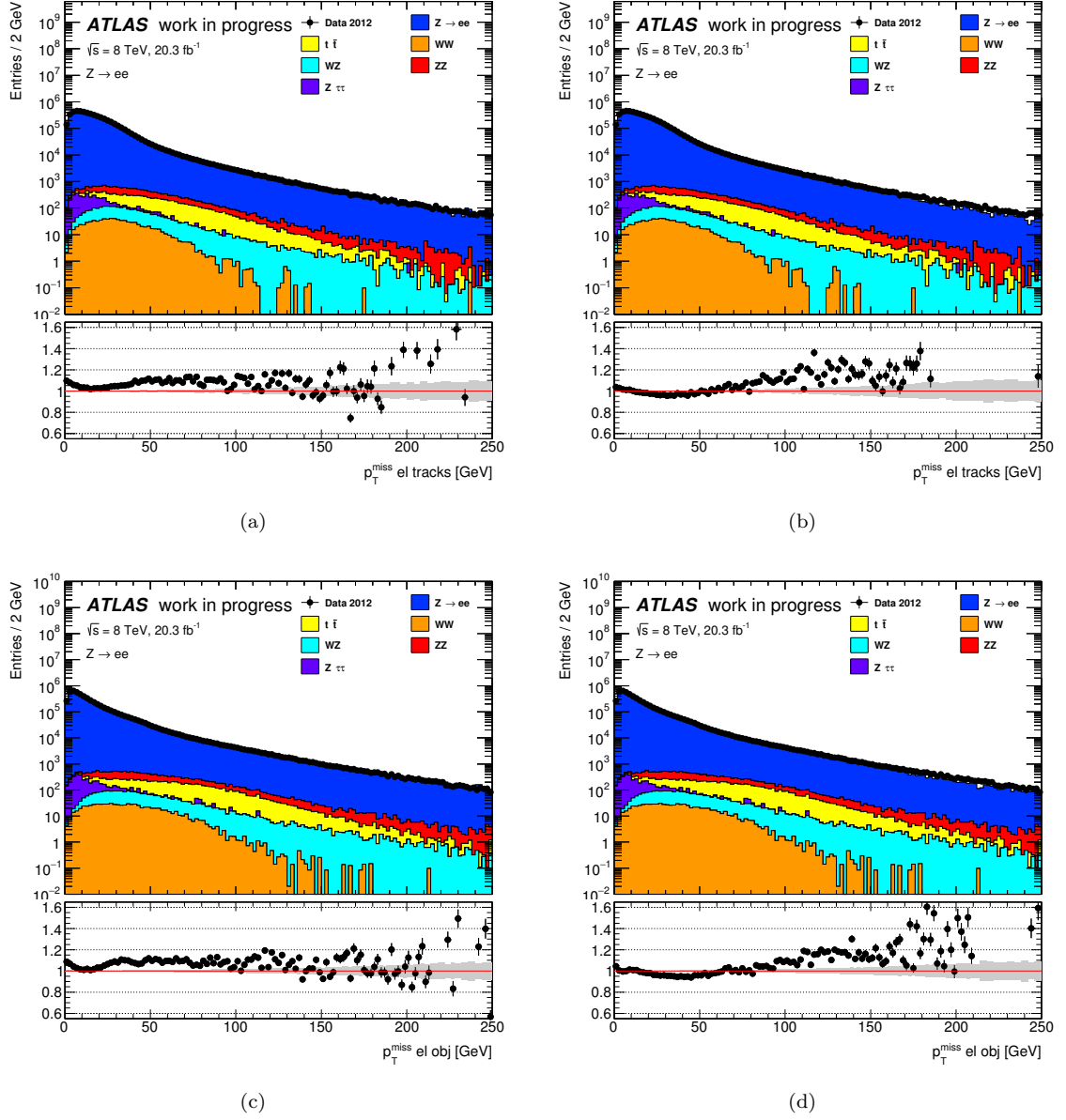


Figure B.10: Electron term modelling in the nominal (top) and object-corrected (bottom) p_T^{miss} , for AlpgenJimmy (left) and PowhegPythia (right).

Glossary

ALICE A Large Ion Collider Experiment, one of the 4 large experiments at the LHC. Its main focus is heavy ion physics.

ATLAS A Toroidal LHC Apparatus, one of the 4 large experiments at the LHC, a general-purpose detector with a range of experimental goals, and one of the two experiments involved in the 2012 discovery of the Higgs boson.

bunch crossing The protons in the LHC are grouped into bunches spaced by 25 ns (at design operation). At the four interaction points that house the large detectors, the LHC beamlines - and hence the proton bunches - cross, resulting in scattering interactions between the protons in the two colliding bunches..

Calorimeter A detector for energy measurement via total particle absorption. The ATLAS Experiment uses both Electromagnetic and Hadronic calorimeters, for measurements of particles that interact via the electromagnetic and strong interactions respectively.

CERN The European Organisation for Nuclear Research, France/Switzerland.

CMS The Compact Muon Solenoid, one of the 4 large experiments at the LHC. A general-purpose detector like ATLAS, and one of the two experiments involved in the 2012 discovery of the Higgs boson.

η Pseudorapidity in the ATLAS coordinate system, given by $\eta = -\log(\tan(\theta/2))$ where θ is the polar angle measured from the beam axis..

$\mathbf{E}_T^{\text{miss}}$ Missing transverse energy, the magnitude of the momentum imbalance in the plane transverse to the proton beam axis, and traditionally calculated from energy deposits in the calorimeter.

eV Electron Volt, a measure of energy equivalent to 1.602×10^{-19} J. Particles can be classified by mass (eV/c^2), momentum (eV/c) or energy (eV), though for ease of use natural units are often used where $c=1$.

ggF Gluon-gluon fusion, the most common Higgs production mechanism that proceeds through a top quark loop since massless gluons do not couple directly to the Higgs field.

ID The ATLAS Inner Detector, a precision particle tracker comprised of three subsystems: the Pixel Detector, a Semiconductor Tracker, and a Transition Radiation Tracker, as well as the solenoid magnet.

jet A boosted cone of (mainly) hadronic particles resulting from the hadronisation of a radiated quark or gluon.

LHC The Large Hadron Collider, a 27 km circumference synchrotron accelerator housing two counter-rotating beamlines.

LHCb The Large Hadron Collider Beauty experiment, one of the 4 large experiments at the LHC with a focus on CP-violating physics.

MS The ATLAS Muon Spectrometer system, comprised of the toroidal magnets and tracking chambers for precision muon momentum measurements and triggering.

$\langle\mu\rangle$ The average number of proton-proton interactions per bunch crossing.

N_{pv} The number of reconstructed primary vertices in a given bunch crossing.

PDF Parton Distribution Function, a function of momentum and energy scale, giving the probability density of finding a parton of a certain type with a given momentum fraction x inside the proton, for a particular energy (resolution) scale Q^2 .

ϕ Azimuthal angle in the ATLAS coordinate system, measured in the plane transverse to the beam-line..

pileup A term referring to the number of non-signal interactions within a given event (bunch crossing). The term most often refers to in-time pileup, which includes all the non-signal interactions within the same bunch crossing as the signal interaction being considered. Out-of-time pileup refers to delayed interactions from particles from earlier bunch crossings that create noise in the detector during the current event.

primary vertex A vertex from the prompt scattering between two protons in a single bunch crossing with a small transverse distance from the beamline. The main (signal) primary vertex in the ATLAS reconstruction algorithm is considered to be the vertex with the hardest scattering, characterised by the highest $\sum(p_T^{track})^2$.

$\mathbf{p}_T$ Transverse momentum, measured in the plane perpendicular to the beamline.

$\mathbf{p}_T^{\text{miss}}$ Missing transverse momentum from tracks, the magnitude of the momentum imbalance in the plane transverse to the proton beam axis calculated from charged particle tracks in the Inner Detector.

Q^2 The square of the four-momentum transfer, which is a measure of the energy scale (or resolution) of an interaction.

Standard Model The Standard Model of particle physics, an effective quantum field theory that describes all the fundamental particles necessary to describe the universe we observe today (with a few limitations).

$t\bar{t}H$ Higgs production in association with top quarks (also b quarks, though much more rarely), where the incoming gluons fluctuate into $t\bar{t}$ pairs, and a top quark from each pair combine to form a Higgs boson.

VBF Vector boson fusion, a Higgs production mechanism where radiated vector bosons combine to form the Higgs boson, leaving a characteristic additional signal of two well-separated jets from the incoming quarks.

VH Higgs production in association with a vector boson (Higgs-strahlung), where quark-antiquark scattering produces a vector boson which radiates a Higgs boson.

x The fraction of the momentum of the proton carried by an individual parton.

Bibliography

- [1] L. Evans and P. Bryant, *LHC Machine*, JINST **3** (2008) S08001.
- [2] ATLAS Collaboration, G. Aad et al., *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.
- [3] ALICE Collaboration, K. Aamodt et al., *The ALICE experiment at the CERN LHC*, JINST **3** (2008) S08002.
- [4] CMS Collaboration, S. Chatrchyan et al., *The CMS experiment at the CERN LHC*, JINST **3** (2008) S08004.
- [5] LHCb Collaboration, J. Alves, A. Augusto et al., *The LHCb Detector at the LHC*, JINST **3** (2008) S08005.
- [6] ATLAS Collaboration, *Search for the Standard Model Higgs boson in produced in association with a vector boson and decaying to bottom quarks with the ATLAS detector*, Tech. Rep. ATLAS-CONF-2012-161, CERN, Geneva, Nov, 2012.
- [7] ALEPH Collaboration, CDF Collaboration, D0 Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, SLD Collaboration, LEP Electroweak Working Group, Tevatron Electroweak Working Group, SLD Electroweak and Heavy Flavour Groups, *Precision Electroweak Measurements and Constraints on the Standard Model*, [arXiv:1012.2367 \[hep-ex\]](#).
- [8] Particle Data Group, K. Olive et al., *Review of Particle Physics (RPP)*, Chin. Phys. C **38** (2014).
- [9] B. R. Martin and G. Shaw, *Particle Physics*. John Wiley & Sons Ltd, 2008.
- [10] A. Martin, W. Stirling, R. Thorne, and G. Watt, *Parton distributions for the LHC*, Eur.Phys.J. **C63** (2009) 189–285, [arXiv:0901.0002 \[hep-ph\]](#).
- [11] G. Altarelli and G. Parisi, *Asymptotic Freedom in Parton Language*, Nucl.Phys. **B126** (1977) 298.

- [12] Y. L. Dokshitzer, *Calculation of the Structure Functions for Deep Inelastic Scattering and $e+e-$ Annihilation by Perturbation Theory in Quantum Chromodynamics.*, Sov.Phys.JETP **46** (1977) 641–653.
- [13] V. Gribov and L. Lipatov, *Deep inelastic $e p$ scattering in perturbation theory*, Sov.J.Nucl.Phys. **15** (1972) 438–450.
- [14] LHCb collaboration, R. Aaij et al., *Test of lepton universality using $B^+ \rightarrow K^+ \ell^+ \ell^-$ decays*, arXiv:1406.6482 [hep-ex].
- [15] R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, *FEWZ 2.0: A code for hadronic Z production at next-to-next-to-leading order*, Comput.Phys.Commun. **182** (2011) 2388–2403, arXiv:1011.3540 [hep-ph].
- [16] A. Buckley, J. Butterworth, S. Gieseke, D. Grellscheid, S. Hoche, et al., *General-purpose event generators for LHC physics*, Phys.Rept. **504** (2011) 145–233, arXiv:1101.2599 [hep-ph].
- [17] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, et al., *New parton distributions for collider physics*, Phys.Rev. **D82** (2010) 074024, arXiv:1007.2241 [hep-ph].
- [18] ATLAS Collaboration, *New ATLAS event generator tunes to 2010 data*, 2011.
- [19] ATLAS Collaboration, *ATLAS tunes of PYTHIA 6 and Pythia 8 for MC11*, 2011.
- [20] ATLAS Collaboration, *Further ATLAS tunes of PYTHIA6 and Pythia 8*, 2011.
- [21] J. M. Campbell and R. Ellis, *MCFM for the Tevatron and the LHC*, Nucl.Phys.Proc.Suppl. **205-206** (2010) 10–15, arXiv:1007.3492 [hep-ph].
- [22] T. Sjostrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, JHEP **0605** (2006) 026, arXiv:hep-ph/0603175 [hep-ph].
- [23] T. Sjostrand, S. Mrenna, and P. Z. Skands, *A Brief Introduction to PYTHIA 8.1*, Comput.Phys.Commun. **178** (2008) 852–867, arXiv:0710.3820 [hep-ph].
- [24] P. Golonka and Z. Was, *PHOTOS Monte Carlo: A Precision tool for QED corrections in Z and W decays*, Eur.Phys.J. **C45** (2006) 97–107, arXiv:hep-ph/0506026 [hep-ph].
- [25] G. G. I. G. Andersson, B. and T. Sjostrand, *Parton Fragmentation and String Dynamics*, Phys. Rep. **97** (1983) 31–145.
- [26] G. Corcella, I. Knowles, G. Marchesini, S. Moretti, K. Odagiri, et al., *HERWIG 6: An Event generator for hadron emission reactions with interfering gluons (including supersymmetric processes)*, JHEP **0101** (2001) 010, arXiv:hep-ph/0011363 [hep-ph].

- [27] A. Kupco, *Cluster hadronization in HERWIG 5.9*, arXiv:hep-ph/9906412 [hep-ph].
- [28] J. Butterworth, J. R. Forshaw, and M. Seymour, *Multiparton interactions in photoproduction at HERA*, Z.Phys. **C72** (1996) 637–646, arXiv:hep-ph/9601371 [hep-ph].
- [29] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. D. Polosa, *ALPGEN, a generator for hard multiparton processes in hadronic collisions*, JHEP **0307** (2003) 001, arXiv:hep-ph/0206293 [hep-ph].
- [30] S. Frixione and B. R. Webber, *Matching NLO QCD computations and parton shower simulations*, JHEP **0206** (2002) 029, arXiv:hep-ph/0204244 [hep-ph].
- [31] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, JHEP **0411** (2004) 040, arXiv:hep-ph/0409146 [hep-ph].
- [32] S. Frixione, P. Nason, and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, JHEP **0711** (2007) 070, arXiv:0709.2092 [hep-ph].
- [33] S. Alioli, P. Nason, C. Oleari, and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP **1006** (2010) 043, arXiv:1002.2581 [hep-ph].
- [34] *ATLAS: letter of intent for a general-purpose pp experiment at the large hadron collider at CERN*, Tech. Rep. CERN-LHCC-92004, 1992.
- [35] ATLAS Collaboration, W. Armstrong et al., *ATLAS: Technical proposal for a general-purpose p p experiment at the Large Hadron Collider at CERN*, 1994.
- [36] ATLAS, G. Aad et al., *Improved luminosity determination in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector at the LHC*, Eur.Phys.J. **C73** no. 8, (2013) 2518, arXiv:1302.4393 [hep-ex].
- [37] ATLAS Collaboration, *Improved Luminosity Determination in pp Collisions at $\sqrt{s} = 7$ TeV using the ATLAS Detector at the LHC*, 2012.
- [38] ATLAS Collaboration, *Data-Quality Requirements and Event Cleaning for Jets and Missing Transverse Energy Reconstruction with the ATLAS Detector in Proton-Proton Collisions at a Center-of-Mass Energy of $\sqrt{s} = 7$ TeV*, 2010.
- [39] ATLAS Collaboration, *ATLAS inner detector: Technical design report. Vol. 1*, 1997.
- [40] ATLAS Collaboration, *ATLAS inner detector: Technical design report. Vol. 2*, 1997.
- [41] T. Cornelissen, M. Elsing, S. Fleischmann, W. Liebig, E. Moyse, et al., *Concepts, Design and Implementation of the ATLAS New Tracking (NEWT)*, 2007.

- [42] *Alignment of the ATLAS Inner Detector and its Performance in 2012*, Tech. Rep. ATLAS-CONF-2014-047, CERN, Geneva, Jul, 2014.
- [43] ATLAS Collaboration, *Performance of primary vertex reconstruction in proton-proton collisions at $\sqrt{s}=7$ TeV in the ATLAS experiment*, 2010.
- [44] ATLAS Collaboration, *Performance of the ATLAS Inner Detector Track and Vertex Reconstruction in the High Pile-Up LHC Environment*, 2012.
- [45] ATLAS Collaboration, *ATLAS liquid argon calorimeter: Technical design report*, 1996.
- [46] ATLAS Collaboration, *ATLAS tile calorimeter: Technical design report*, 1996.
- [47] ATLAS Collaboration, *ATLAS muon spectrometer: Technical design report*, 1997.
- [48] ATLAS Collaboration, *Summary of ATLAS Pythia 8 tunes*, 2012.
- [49] GEANT4, S. Agostinelli et al., *GEANT4: A Simulation toolkit*, Nucl.Instrum.Meth. **A506** (2003) 250–303.
- [50] ATLAS Collaboration, G. Aad et al., *The ATLAS Simulation Infrastructure*, Eur.Phys.J. **C70** (2010) 823–874, [arXiv:1005.4568](#) [[physics.ins-det](#)].
- [51] CDF Collaboration, F. Abe et al., *Jet fragmentation properties of $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV*, Phys.Rev.Lett. **65** (1990) 968–971.
- [52] ATLAS Collaboration, G. Aad et al., *Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC*, New J.Phys. **13** (2011) 053033, [arXiv:1012.5104](#) [[hep-ex](#)].
- [53] ATLAS Collaboration, *Measurement of the missing transverse momentum based on tracks in proton-proton collisions at $\sqrt{s}=900$ GeV centre-of-mass energy with the ATLAS detector*, 2010.
- [54] M. Cacciari and G. P. Salam, *Pileup subtraction using jet areas*, Phys.Lett. **B659** (2008) 119–126, [arXiv:0707.1378](#) [[hep-ph](#)].
- [55] ATLAS Collaboration, G. Aad et al., *Muon reconstruction efficiency and momentum resolution of the ATLAS experiment in proton-proton collisions at $\sqrt{s}=7$ TeV in 2010*, Eur.Phys.J. **C74** (2014) 3034, [arXiv:1404.4562](#) [[hep-ex](#)].
- [56] ATLAS Collaboration, G. Aad et al., *Electron efficiency measurements with the ATLAS detector using the 2012 LHC proton-proton collision data*, 2014.
- [57] ATLAS Collaboration, G. Aad et al., *Electron reconstruction and identification efficiency*

- measurements with the ATLAS detector using the 2011 LHC proton-proton collision data*, Eur.Phys.J. **C74** (2014) 2941, [arXiv:1404.2240](#) [hep-ex].
- [58] M. Cacciari, G. P. Salam, and G. Soyez, *The Anti- $k(t)$ jet clustering algorithm*, JHEP **0804** (2008) 063, [arXiv:0802.1189](#) [hep-ph].
- [59] ATLAS Collaboration, G. Aad et al., *Jet energy measurement with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV*, Eur.Phys.J. **C73** (2013) 2304, [arXiv:1112.6426](#) [hep-ex].
- [60] ATLAS Collaboration, G. Aad et al., *Jet energy measurement and its systematic uncertainty in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, [arXiv:1406.0076](#) [hep-ex].
- [61] ATLAS Collaboration, G. Aad et al., *Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics (Jet and E_T^{miss} Chapter)*, [arXiv:0901.0512](#) [hep-ex].
- [62] C. Adam-Bourdarios and S. S. et al, *EM Calorimeter Calibration and Performance*, 2008.
- [63] P. S. et al, *Performance of Overall Calorimetry Energy Reconstruction: Hadronic Calibration H1, Topo Cluster Classification*, 2008.
- [64] W. Lampl, S. Laplace, D. Lelas, P. Loch, H. Ma, et al., *Calorimeter clustering algorithms: Description and performance*, 2008.
- [65] ATLAS Collaboration, G. Aad et al., *Performance of Missing Transverse Momentum Reconstruction in Proton-Proton Collisions at 7 TeV with ATLAS*, Eur.Phys.J. **C72** (2012) 1844, [arXiv:1108.5602](#) [hep-ex].
- [66] ATLAS Collaboration, G. Aad et al., *Performance of Missing Transverse Momentum Reconstruction in ATLAS studied in Proton-Proton Collisions recorded in 2012 at 8 TeV*, 2013.
- [67] R. Aben, H. Abouzeid, J. Alison, M. Antonelli, M. Aoki, A. Armbruster, O. Arnaez, A. Barbaro Galtieri, T. Baroncelli, J. Barreiro Guimaraes da Costa, A. Belloni, E. Berglund, R. Bernhard, M. Biglietti, V. Bortolotto, A. Boveia, B. Brelier, J. Bronner, F. Canelli, B. Cerio, P. Chang, M. A. Chelstowska, S. Chen, B. Chow, G. Conti, P. Dang, B. Di Micco, R. di Nardo, S. Diglio, M. Duehrssen, J. Elmsheuser, A. Farilla, E. Feng, P. Ferrari, F. Fiedler, F. Filthaut, S. Gadatsch, J. Griffiths, P. Guenther, D. Hall, A. Harb, F. Hariri, C. Hays, Y. Hernandez, T. M. Hong, J. Howard, P. J. Hsu, N. Ilic, M. Iodice, K. Jakobs, S. Jin, J. Jovicevic, A. Kaluza, N. Karastathis, L. Kashif, R. Kehoe, J. Keung, H. Kim, T. Kishimoto, P. Kluit, A. Kotwal, P. Krieger, J. Kroll, T. Kubota, J. Kunkle, T. Lazovich, C. Lee, T. Lenz, C. Lester, H. Li, S. Li, Y. Li, Z. Liang, E. Lipeles, J. Long, L. Ma, J. T. Machado Miguéns, T. Masubuchi, T. Matsushita, J. Mattmann, R. Mazini, C. Meineck, C. Melachrinou, B. Mellado, C. Mills, S. Moritz, M. Neubauer, W. Okamura, P. Onyisi, D. Orestano, R. Ospanov, S. Pagan Griso, Y. Pan, H. Peng, D. Pershey, F. Petrucci, R. Polifka, J. Qian, W. Quayle, P. Rados, B. Ramson, X. Ruan, R. Sandstrom, P. Savard, D. Schaefer, E. Schmidt, C. Schmitt, D. Schouten, M. Shochet, H. Skottowe, K. Sliwa,

- W. Spearman, B. Stelzer, O. Stelzer-Chilton, J. Strandberg, M. Testa, R. Teuscher, R. Thun, Y. Tsipolitis, I. Tsukerman, J. Valls, J. van Nieuwkoop, R. Vanguri, M. Venturi, N. Venturi, W. Verkerke, T. Vu Anh, S. Walch, A. Walz, C. Weiser, J. Wetter, G. Wooden, S. L. Wu, K. Yoshihara, J. Yu, Z. Zhang, Z. Zhao, and Y. Zhu, *Analysis of $H \rightarrow WW(*) \rightarrow \ell\nu\ell\nu$ in the same-flavour channels*, Tech. Rep. ATL-COM-PHYS-2012-1445, CERN, Geneva, Sep, 2012.
- [68] ATLAS Collaboration, *Observation and measurement of Higgs boson decays to WW^* with the ATLAS detector*, [arXiv:1412.2641](#) [hep-ex].
- [69] ATLAS Collaboration, G. Aad et al., *Search for the Higgs boson in the $H \rightarrow WW(*) \rightarrow \ell\nu\ell\nu$ decay channel in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, Phys.Rev.Lett. **108** (2012) 111802, [arXiv:1112.2577](#) [hep-ex].
- [70] ATLAS Collaboration, G. Aad et al., *Search for the $b\bar{b}$ decay of the Standard Model Higgs boson in associated $(W/Z)H$ production with the ATLAS detector*, [arXiv:1409.6212](#) [hep-ex].
- [71] ATLAS Collaboration, *Commissioning of the ATLAS high-performance b-tagging algorithms in the 7 TeV collision data*, 2011.
- [72] A. Hocker, J. Stelzer, F. Tegenfeldt, H. Voss, K. Voss, et al., *TMVA - Toolkit for Multivariate Data Analysis*, PoS **ACAT** (2007) 040, [arXiv:physics/0703039](#) [PHYSICS].
- [73] ATLAS Collaboration, G. Aad et al., *Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, [arXiv:1408.7084](#) [hep-ex].
- [74] ATLAS Collaboration, G. Aad et al., *Pile-up Suppression in Missing Transverse Momentum Reconstruction in the ATLAS Experiment in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV*, 2014.
- [75] P. Dirac, *A Theory of Electrons and Protons*, Proc.Roy.Soc.Lond. **A126** (1930) 360.
- [76] M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*. Westview Press, 1995.
- [77] R. P. Feynman, *Very high-energy collisions of hadrons*, Phys.Rev.Lett. **23** (1969) 1415–1417.
- [78] J. Bjorken and E. A. Paschos, *Inelastic Electron Proton and gamma Proton Scattering, and the Structure of the Nucleon*, Phys.Rev. **185** (1969) 1975–1982.
- [79] M. Gell-Mann, *A Schematic Model of Baryons and Mesons*, Phys.Lett. **8** (1964) 214–215.
- [80] G. Zweig, *An $SU(3)$ model for strong interaction symmetry and its breaking. Version 1*, 1964.
- [81] ATLAS Collaboration, G. Aad et al., *Calibration of b-tagging using dileptonic top pair events in a combinatorial likelihood approach with the ATLAS experiment*, 2014.

- [82] ATLAS Collaboration, G. Aad et al., *Calibration of the performance of b-tagging for c and light-flavour jets in the 2012 ATLAS data*, 2014.
- [83] F. Englert and R. Brout, *Broken Symmetry and the Mass of Gauge Vector Mesons*, Phys.Rev.Lett. **13** (1964) 321–323.
- [84] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, Phys.Lett. **12** (1964) 132–133.
- [85] G. Guralnik, C. Hagen, and T. Kibble, *Global Conservation Laws and Massless Particles*, Phys.Rev.Lett. **13** (1964) 585–587.
- [86] J. Goldstone, A. Salam, and S. Weinberg, *Broken Symmetries*, Phys.Rev. **127** (1962) 965–970.
- [87] ATLAS Collaboration, G. Aad et al., *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys.Lett. **B716** (2012) 1–29, [arXiv:1207.7214 \[hep-ex\]](#).
- [88] CMS Collaboration, S. Chatrchyan et al., *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys.Lett. **B716** (2012) 30–61, [arXiv:1207.7235 \[hep-ex\]](#).
- [89] LHC Higgs Cross Section Working Group, S. Dittmaier, C. Mariotti, G. Passarino, and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*, CERN-2011-002 (CERN, Geneva, 2011), [arXiv:1101.0593 \[hep-ph\]](#).